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Material Properties and Characteristics for Development of an Expert System for Coal-Tar Sealers

James E. Shoenberger

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
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Material Properties and Characteristics for Development of an Expert System for Coal-Tar Sealers

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Final report

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PREFACE

The research reported herein was sponsored by the U.S. Army Corps of Engineers through the Research, Development, Testing, and Evaluation (RDT&E) Program and the In-House Laboratory Independent Research (ILIR) Program at the U.S. Army Engineer Research and Development Center (ERDC), Vicksburg, MS.

This study was conducted under the general supervision of Dr. W. F. Marcuson, former Director, Geotechnical and Structures Laboratory (GSL), Dr. Michael J. O'Connor, Director, GSL, Dr. D. W. Pittman, former Chief, Airfields and Pavements Division, Dr. A. J. Bush, Chief, Engineering Systems and Materials Division, and Dr. G. L. Anderton, acting Chief, Airfields and Pavements Branch (APB). Dr. John B. Metcalf, Louisiana State University, provided much insight and technical advice during the testing, analysis, and publication phases of this research. Dr. James E. Shoenberger, APB, was the project principal investigator and author of this report. The APB personnel engaged in the laboratory testing included Messrs. H. Tommy Carr, Rogers Graham, Herbert McKnight, and Roosevelt Felix. Drs. Reed B. Freeman and Donald M. Smith provided technical guidance and assistance during this research. This report was submitted to and accepted by the Graduate School at Louisiana State University as Dr. Shoenberger's dissertation.

At the time of publication of this report, the Director of ERDC was Dr. James R. Houston, and the Commander and Executive Director was COL John W. Morris III, EN.

CHAPTER 1: INTRODUCTION

BACKGROUND

The military has many pavements that are exposed to various types of fuel spillage. This spillage occurs in parking, maintenance, and refueling areas for both aircraft and vehicles. Asphalt pavements are susceptible to spillage of petroleum products because asphalt cement is derived from the same material. These products include: hydraulic fluid, motor oils, diesel, and gasoline. Fuel spilling on an asphalt pavement will soften and leach away the asphalt binder and eventually the pavement will require extensive repairs. The use of Portland cement concrete (PCC) will eliminate the need for fuel resistant sealers; however, for various reasons including: cost, change in mission, and the use of existing pavement structures, it is not feasible to place and use only PCC.

Coal tar is a material that has historically been used as a fuel-resistant binder material for sealers and in some cases for the pavement itself. Coal tar is resistant to fuel spillage from petroleum based materials because it is derived from coal and therefore has a different chemical makeup not greatly affected by petroleum-based materials. The coal tar used to manufacture the road tar (RT) material, which is emulsified for sealer applications, is obtained as a by-product of the production of coke used as a fuel in the production of steel. Road tars are more temperature susceptible (change in viscosity for an equal change in temperature) than asphalt cements. However, a cured coal-tar emulsion shows almost no temperature susceptibility. Also, there are no significant health concerns when using coal tars in emulsion form.

Research into the design and performance of coal tar and coal-tar sealers has been limited. Historically, the larger producers conducted the majority of research on coal tar materials. Over the last few decades, these producers cut back or eliminated much of their research. There have been a few government-sponsored investigations and the sealer industry has recently begun funding some long-term research at a major university. Generally, the relatively low investment required for sealers, compared to the overall cost of the pavement itself, has probably contributed to the low priority of research in sealer materials. However, sealer materials can extend the life of a pavement structure and a fuel-resistant sealer is required for most parking and maintenance areas where fuel spillage might occur. The ultimate goal of any research in this area would be the development of performance-based specifications for fuel-resistant sealers for hot-mix asphalt pavements.

Currently, an engineer/designer of fuel-resistant (coal-tar) sealer surfacings must decide which mixture components and their amounts to specify. The development of an expert system to facilitate the development of pertinent construction specifications would be useful to the military and others with pavements exposed to fuel spillage.

OBJECTIVES

The research described in this report was conducted and analyzed to achieve the following objectives:

- To review current state-of-the-art methods and procedures used to design and test coal tar sealers.

- To evaluate the material properties of coal tar sealer materials and mixtures both new and after aging.
- To develop relationships between the material properties of the coal tar materials and the observed field performance of various coal tar sealer mixtures.
- To develop an expert system to use the information obtained to develop a specification for coal-tar sealers that will provide optimum field performance.
- To develop a new guide specification that in conjunction with the expert system will provide a satisfactory coal-tar sealer.

SCOPE

This report contains a review of current practice and recent research concerning fuel-resistant sealers for asphalt pavements. A field and laboratory evaluation was conducted on coal-tar emulsion and polymer additives from two manufacturers. A common type of aggregate (silica sand), of the size normally specified for airfield applications, was used in the various mixtures. Variables evaluated in the mixtures included: the amount of polymer additive, the amount of aggregate, and the application rate. A field test section was placed and evaluated for over two years, until the time of this report. Laboratory testing was conducted, on the same materials and in the same proportions, using newly developed test methods. The evaluation involved the use of several test methods, developed as part of the Strategic Highway Research Program (SHRP), with minor adjustments, and other methods and procedures that were developed for this study. The SHRP methods used were the

Bending Beam Rheometer and the dynamic shear rheometer. These methods provide information on the rheological properties of coal-tar materials and mixtures. The methods and procedures developed were used to measure the aging, thermal, and tensile strength and stress-relaxation properties of the coal-tar mixtures.

Unresolved issues concerning the stress/strain behavior of the sealers during relatively small thermal movements and in defining the formation and progress of cracks within the coal-tar sealer prevented the development of a satisfactory practical mechanistic explanation of the cracking. Instead, the information obtained from this study was used to develop an expert system for the material selection, design, and construction of a coal-tar sealer. A guide specification incorporating all information obtained on coal-tar sealers is included as Appendix D and the screens and code used for the expert system are given in Appendix E.

CHAPTER 2: LITERATURE REVIEW

INTRODUCTION

Coal-tar emulsions have been used as pavement sealers for many years. In the late 1930s the first emulsified coal tar was developed containing a refined coal tar, water, clay, and some emulsifying (wetting) agent. Other manufacturers developed similar products and this eventually led to the development of a Federal Specification (Federal Specification 1957). Currently, the American Society for Testing and Materials (ASTM) standard specification D 5727 for emulsified coal tar is largely based on this federal standard (ASTMa 1999). The majority of published research, in regard to coal tar materials was carried out by the major manufacturers of coal tar during the time period from the 1930s to the 1960s. For this reason, the majority of information concerning the engineering properties of coal tar was published before 1960. Coal-tar emulsion systems were developed in the early 1950s. The only major change in these systems has been the introduction of a polymer material to the sealer mixture. In recent years, there have been a few research studies concerning coal-tar emulsion mixtures for pavement sealer applications.

USES OF COAL-TAR SEALERS

Coal-tar sealers are used to protect hot-mix asphalt pavements from the detrimental effects of fuel spillage. The requirement of a coal-tar sealer for automobile vehicle-parking areas can be based on the number of vehicle turnovers within a given time frame. This means locations where many vehicles use a given pavement location usually require a coal-tar sealer because vehicle engines, are subject to fuel spillage or drippage mainly when they are hot. Therefore, locations

where vehicles park for the day or for extended periods of time normally do not experience enough spillage to justify the use of a coal-tar sealer. Maintenance and refueling areas are expected to experience spillage from normal operations or from accidents and thereby require coal-tar sealers. On many military bases these areas are equipped with some type of collection system to prevent any petroleum material runoff from spillage or carried by a rain event from leaving the containment area.

SPECIFICATIONS

Specifications for coal-tar emulsion mixtures have historically centered on prescriptive mixture requirements. The basic materials are required to meet given material properties, usually defined through ASTM, AASHTO, or other standards. The mixture is selected from a given range of materials (i.e., coal-tar emulsion, water, and aggregate). A study in the late 1980s (Shook et al. 1990) developed a series of test methods for the design of a coal-tar sealer. The Corps of Engineers (CE) has historically performed research on coal-tar emulsion sealers (Hansen 1959a). This research led to the development of guide specifications for both plain and latex-modified sealers. These specifications required a flexibility test for the design mixture, one of the first instances of the use of a performance based test method. The current guide specification provides several test requirements that the sealer mixture must satisfy but does not give a range of materials (USACE 1988). It is an accepted industry standard to reference the current ASTM standard D 5727 to specify the coal-tar emulsion.

The development of test methods to evaluate specific properties of coal-tar materials continues within the sealer industry. Currently, ASTM standard D2939 contains the majority of the test methods that are referenced for coal tar material

testing (ASTM 1999). The sealer industry has recently begun to invest in research and has established an industry funded research group called the Pavement Coatings Technology Center (PCTC) at the University of Nevada at Reno. The PCTC is supported by a group of manufacturers to investigate methods of refining and improving coal-tar mixtures. They have produced recommended guide specifications and have released reports dealing with several proposed test methods, which are currently being incorporated into applicable ASTM standards.

TEMPERATURE EFFECTS

Coal tar sealers and the underlying pavement structure are affected by thermal changes. The thermal changes occur on almost a continual basis and will often cycle through similar temperatures over a 24-hour period. Various researchers have developed models to deal with the temperature changes that occur on and within the pavement structure. The majority of these models are based on the amount of solar radiation or other energy transfer effects (Barber 1957 and Solaimanian and Kennedy 1993). The effect of temperature change with depth has also been investigated (Southgate and Deen 1969). Temperature profiles of asphalt pavements have been developed through field measurements. The results of these investigations show, that as expected, the temperature changes are most extreme at the pavement surface. The temperature of the pavement surface depends upon many factors including the air temperature, the amount of solar radiation (sunlight), humidity, latitude, and wind speed. With increasing depth, the temperature of the pavement increasingly lags behind the air temperature and does not cycle through the extreme changes as the surface (Monismith, Secor, and Secor 1965; Solaimanian and Kennedy 1993; and Mohseni 1998).

As part of the SHRP-developed SUPERPAVE system, a long-term pavement performance (LTPP) study was initiated in the early 1990s. A seasonal monitoring program (SMP) was conducted from air and pavement temperatures collected at various sites throughout the U.S. The results of this investigation were the development of temperature models for both low and high temperature conditions (Mohseni 1998). These models were developed through a statistical analysis of the SMP database. The models were selected because of their goodness of fit (coefficient of correlation, R^2), variability (standard error of estimate, SEE), and boundary conditions. The equations as given for determining low and high pavement temperatures have been adjusted for latitude of 32.6 degrees, at Vicksburg, MS.

Low Temperatures:

$$T_{\text{pav}} = -1.56 + 0.72 T_{\text{air}} - 4.251 + 6.26 \log_{10} (H+25)$$

High Temperatures:

$$T_{\text{pav}} = 54.32 + 0.78 T_{\text{air}} - 2.657 - 15.14 \log_{10} (H+25)$$

where

T_{pav} = Asphalt pavement temperature below the surface, °C

T_{air} = Air temperature

H = Depth from surface, mm

Coal-tar sealers tend to be and remain substantially darker in color than hot-mix asphalt pavement surfaces. Because of this the amount of solar radiation absorbed is greater and therefore these surfaces have higher temperatures than adjoining, somewhat lighter color, asphalt pavement surfaces.

MATERIAL PROPERTIES

Coal tar sealers are a combination of emulsified coal tar, sand, and water.

Emulsified coal tar is a combination of a road tar, clay, emulsifying agents, and water. Currently, all road tars and therefore coal-tar emulsions are obtained from the production of coke for the steel production industry. The tar from this process is used because it is more inert and absorbs water less readily than coal tars obtained from horizontal-retorts, water-gas, or oil-gas processes (Stoner 1996). Coke is manufactured through the thermal decomposition of coal, with temperatures reaching about 1,200°C (2,200°F) (Hunter 1994). During this process heavy pitches and various distillates are recovered. Various grades of road tar (RT) are formulated by a blending process of the various coal-tar oils and pitches (Hoiberg 1966a). The various grades of road tar (RT-1 through RT-12) are defined in ASTM D 490 (ASTMc 1999). Today, RT-12 is the base material used in the manufacture of coal-tar emulsions. Another grade of road tar would be used only under unusual circumstances. In the U.S. there are currently about five companies that supply RT-12 coal tar. These companies generally have access not only to domestically produced coal tar, but also to coal tar produced worldwide. Several of these companies also produce their own emulsions, but generally other emulsion manufacturing companies purchase the RT-12 and produce their own coal-tar emulsion. Depending on price and availability, an emulsion manufacturer may purchase RT-12 from several different suppliers throughout a given time frame.

Coal tar is well known for its ability to adhere or bond to various materials, including aggregate, even in high moisture conditions (Hoiberg 1966a, Hunter 1994,

and Stoner 1996). Coal tar materials have historically been used as coatings for protection against moisture and oxidation. The composition of coal tar is more than 90 percent carbon (Stoner 1996). The exact chemical makeup of coal tar is very complex. Evaluation by fractionation of the portion of refined coal tars that are sufficiently volatile to distill without decomposition resulted in the identification of 127 different compounds (Hoiberg 1966a). Coke-oven coal tar has a particle size of from 1.8 to 4.0 microns (Volkman, Rhodes, and Work 1936).

Coal-tar emulsions are colloid systems that use clay to hold the binder in suspension with the water. Clay-water slurry is combined with the RT-12 in a high shear mixing operation. There are several different sources of the clay, although it is usually a type of bentonite clay. An emulsifying agent is not specifically required in the emulsification process, although they are used by most manufacturers.

ENVIRONMENTAL CONSIDERATIONS

Coal-tar emulsions have a volatile organic compound (VOC) content that is essentially zero and are not considered toxic or hazardous materials (Stoner 1996). Coal tar is more aromatic than asphalt cement; however, being more susceptible to temperature changes, it does not have to be heated as high as asphalt cement to achieve a corresponding level of viscosity (Puzinauskas and Corbett 1978). An RT-12 at 200 °C would normally have the approximate viscosity of AC-30 graded asphalt cement at 250°C (Hoiberg 1966a).

Puzinauskas and Corbett (1978) reported that evidence from health studies indicated that asphalt cement was not harmful, but that coal tar had not been evaluated sufficiently for a judgment. A coal tar industry study of coal tar sealer materials

showed that airborne concentrations of all compounds tested were below applicable Permissible Exposure Limits (PELs) as established by the Occupational Safety and Health Administration (OSHA) (Heydorn 1992). Neither OSHA nor the Environmental Protection Agency (EPA) classifies coal-tar emulsion sealers as carcinogenic (Heydorn 1992). At this time there are no regulations that would restrict or eliminate the use of coal tar (Montle 1995).

There are several common sense procedures that should be followed when handling coal tar sealers. These include using eye protection and avoiding direct contact with the skin. The following is a listing of general handling procedures when using coal tar sealers (Heydorn 1992 and Stoner 1996):

- Read the Material Safety Data Sheet and/or product label.
- If contact with skin occurs, wash with soap or waterless cleaners.
- Wear full-length clothing (long sleeve shirts and long pants).
- Wear chemical-resistant or liquid-repellant gloves.
- Wear a barrier cream formulated for coal tar products or a general-purpose barrier cream in conjunction with a No. 15 sun lotion.

The concern with run-off of coal tar emulsion sealers would be similar to that associated with asphalt emulsions. As with asphalt emulsions, construction should avoid freezing temperatures or rainfall prior to the emulsion curing to prevent any problems. Depending on climatic conditions and the rate of application, a coal-tar emulsion sealer mixture will generally cure to a stable condition within 1 to 8 hours.

DURABILITY

The exact process through which coal tar materials age or harden has been a source of disagreement for many years. Since the 1930s through the 1960s the main disagreement was between researchers with Koppers, Inc., a coal tar producer, and the Road Research Laboratory in Great Britain. Researchers with Koppers found the coal tar aged mainly through evaporation and to a lesser degree oxidation (McGovern 1949, Rhodes 1949, and Rhodes and Gillander 1936). The Koppers researchers concluded that evaporation had 100 times the effect of oxidation on the properties of coal tar. Researchers in Great Britain reached the opposite conclusion by stating that oxidation and not evaporation was the main cause of hardening in coal tar (Rhodes 1949 and RRL 1962). Both groups of researchers agree that sunlight has almost no effect and water only a slight effect on the properties of coal tar (McGovern 1949, Rhodes 1949, Rhodes and Gillander 1936, and RRL 1962). The differences between the results of both groups were eventually contributed to the use of coal tars obtained from the coal-oil gas industry in Great Britain and those obtained from coke ovens in the U.S. (RRL 1962 and Hoiberg 1966a). The testing performed by Koppers to establish the effect of various parameters on the material properties of coal tar, including evaporation, oxidation, light, and water, were performed between 30 and 40°C. The evaluation of the changes in material properties was determined through the use of the softening point as determined by the ring and ball method.

It has been reported that coal tar materials shrink as they cure and age and that this results in the formation of hairline cracks (Cobb and Krishon 1986). The addition of various polymers, copolymers, or other additives to the coal tar has been proposed

to minimize this shrinkage and resultant cracking (Cobb and Krishon 1986 and Krishon 1987).

Compared to asphalt cement, coal tar is not self-healing and tends to alligator crack faster than asphalt sealers. Coal tar films are less permeable and they have good resistance to weak mineral acids, alkalis, salts, brine solutions, and other aggressive chemicals (Stoner 1996).

CRACKING

Coal-tar sealers provide satisfactory fuel resistance; however, their useful life has been less than satisfactory due to cracking. This cracking occurs almost uniformly throughout a sealed area, apparently unaffected by traffic patterns. This suggests that the probable cause of the cracking is excessive stress or movement due to environmental factors, such as temperature or moisture changes and, changes in the material properties of the sealer.

In the 1950s some emulsions had polymers added to the coal tar prior to emulsification and, starting in the 1970s, increasing numbers of sealers were placed with a polymer added to the coal-tar emulsion in the field. Neither of these approaches has had a significant effect in reducing the amount of cracking.

Coal tar, even RT-12 grade, has greater temperature susceptibility when compared to an asphalt cement binder (Hunter 1994). This means that, compared to asphalt cement, the coal tar becomes stiffer faster at low temperature and softer faster at high temperatures. After an RT-12 has been combined with clay, water, and some emulsifying additives, this temperature susceptibility is greatly reduced (Hansen 1959b). After curing, the coal tar sealer acts like a thermosetting binder, in that high temperatures do not appreciably soften it and it will not flow. On obtaining this very

stable condition the sealer is ideal to withstand the effects of high surface-stress traffic; however, it appears to lose its ability for stress relief (becomes too stiff) and becomes susceptible to thermal movements that cause cracking. Asphalt binders, even as they harden with age, will retain the ability to flow and self heal (stress relax) especially at higher temperatures. However, coal-tar emulsion materials do not flow, even at very high temperatures, and therefore do not possess the same ability for self-healing or stress relaxing. Sealers placed in locations that never receive temperatures below freezing crack in much the same manner as those placed in much colder climates.

MIXTURE STUDIES

In the mid 1980s, the Federal Aviation Administration (FAA) funded a study on coal tar emulsion seal coats (Shook et al. 1989). Due to problems encountered with coal-tar sealers meeting existing specifications, the study was designed to obtain information on field performance and conduct laboratory testing on sealers to determine the specification modifications required for improved performance. The study had two phases, the first being a state of the art review of existing literature, test methods, construction procedures, and field observations (Shook and Shannon 1987). The second part included a field test section and a laboratory investigation (Shook et al. 1989). Field test section construction was performed in two parts. The first test section, constructed at the start of the research, used mixtures and procedures based on input from several industry material manufacturers. This test section provided information on materials, formulations, and construction practices. The second test section was used to evaluate and validate information obtained from the laboratory-testing program. The first test sections constructed showed substantial cracking within

a two-year period. The second test section was not in place for a long enough period of time to judge the long-term performance.

The laboratory study evaluated various test methods that could be used to investigate different mixture parameters including: workability, rate of set, scuff resistance, cracking, flexibility, adhesion, and fuel resistance. The study produced a set of test procedures and protocols and recommended minimum values of these mixture parameters to produce an acceptable mixture. Six different coal tar emulsions, additives, and aggregate gradations were evaluated. The additives investigated in this study included several acrylonitrile-butadiene (AB) latexes, a proprietary product, and an epoxy resin. The AB latex is the most widely used polymer additive in the sealer industry. The testing also investigated the effect of varying the amount of additive, aggregate, and water added to the mixture. The effects of the different mixture components on the basic test results are described below:

- **Viscosity.** In general, the viscosity decreased with an increase in additive content, regardless of the amount of water and sand. The addition of water reduced the viscosity regardless of the amount of additive and sand. The viscosity of the mixture increased with increasing amounts of sand, independent of additive and water content.
- **Rate of Set and Scuff Resistance.** These properties were measured with a torque device and the torque values increased with increasing amounts of sand. The torque values obtained were independent of additive and

water content. Variations in sand shape and gradation were also investigated, but no trends could be determined for the parameters tested.

- **Cracking.** A freeze-thaw test was used to evaluate the cracking potential of the various mixtures. The results showed that as the overall water content of the mixtures increased so did the severity of the cracking. Increases in the amount of sand, resulted in a decrease in crack severity. An increase in the amount of additive tended to increase the amount of cracking.
- **Flexibility.** Flexibility was evaluated by bending coated specimens over a mandrel. The test method was discontinued after some initial testing revealed that the results were not sensitive to changes in mixture components.
- **Adhesion.** The adhesion test was performed using an adhesive tape to pull off the sealer. The test was not effective in evaluating different mixtures; it was only able to remove some sand particles from the mixtures with the highest sand loadings.
- **Fuel resistance.** Two different types of fuel-resistance tests were performed; however, neither test method was able to show significant trends for any of the mixtures investigated.

In 1992, the FAA published a study on the use of seal coats on airport pavements (Saraf, Majidzadeh, and Kumar 1992). Both coal tar and asphalt seal coats were investigated. Through a survey of over 50 airports, the researchers found that seal coats were most commonly constructed with coal tar. In this survey airport

engineers indicated that coal tar sealers with latex outperformed those without a latex additive. The life of the coal tar sealers was anticipated to be from 3 to 5 years.

As part of this study, several airports were visited to observe the performance of coal tar sealers and obtain material samples for laboratory testing. The researchers investigated the test methods as proposed by Shook et al. to evaluate the coal tar mixtures. Their investigation revealed that addition of a latex additive slightly increased the mixture viscosity, while increases in the amount of sand decreased mixture viscosity with constant additive contents. They also found a definite effect of moisture on the cracking characteristics of coal tar mixtures as determined in the freeze-thaw test. The effect of moisture was determined by performing freeze-thaw tests using a dry- and a wet-test protocol. The wet freeze-thaw test method was more severe. The freeze-thaw tests indicated that the latex additive may help delay the occurrence of initial cracking but has less effect on the final overall amount of cracking. The researchers found that mixtures with coarser sands, those with material retained on the 1.18 mm (No. 16) and 850 μm (No. 20) sieve, failed the adhesion test but passed the freeze-thaw test. The test methods did not determine a particular value or quantity for the materials in a mixture, but rather indicated a range of values.

The study concluded that mixtures with sand gradations with high percentages passing the 425 μm (No. 40) sieve tend to require less sand and more additive to produce an acceptable mixture. A latex additive can improve the wet freeze-thaw properties of the coal tar sealer mixture. The latex additive used must be compatible with the coal tar emulsion and the materials must be mixed together prior to adding the sand to the mixture. The freeze-thaw test method, either wet or dry, showed the

greatest promise for measuring the relative performance of various mixtures. Saraf et al. concluded that coal tar sealers should be applied to an asphalt concrete surface prior to the occurrence of surface cracking and a new pavement should be cured at least 6 months prior to sealing (Saraf, Majidzadeh, and Kumar 1992).

MIXTURE PROPORTION PRACTICES

Coal tar sealers are currently proportioned through general guidelines or ranges of the basic materials and through previous experience. The general guidance usually gives a range of water, aggregate, and additive (if used) for each gallon of coal tar emulsion. No procedure for the determination of a particular amount of any of the components of a seal coat mixture has been developed. The procedure developed by the FAA (Shook et al. 1990) only provides a mixture acceptance regimen and not a design procedure. The reported sealer mixture component amounts are usually based on 100 liters (gal) of the emulsified coal tar material.

The amount of water added to the mixture is usually in the range of 10 to 30 percent or 10 to 30 liter (gal) of water per 100 liter (gal) of coal-tar emulsion. The amount used depends on the amount and size of the aggregate used and whether a polymer additive is used. In the field the amount of water may be increased 1 to 3 percent if it is a hot, sunny day. In general, as more water is added to the sealer mixture and the application rate remains constant, the resulting cured coal tar sealer will be thinner.

Aggregate is added to the sealer mixture to provide the sealed surface with adequate skid resistance. Other benefits that may be important, depending on the use of the pavement, include: increased the life of the coating under traffic, decreased curing time, and improved appearance (by making pavement variations, cracks,

patches, etc. more difficult to see). The basic question for mixture proportioning concerning aggregates is the determination of the maximum particle size or aggregate gradation and the amount used in the mixture.

The aggregate gradation used should contain a range of particle sizes to provide a dense and strong structure in the cured surface. The maximum particle size that can be used is controlled by the amount of sealer material and moisture in each layer that is applied. The uncured sealer should be applied in a depth greater than the diameter of the maximum sized particle and the cured surface should have a depth sufficient to completely or at least nearly embed these particles. For most applications this requires that the aggregates completely pass the 1.18 mm (No. 16) or 850 μm (No. 20) sieves. Larger aggregate particles can increase the possibility of aggregates falling out of suspension and 'streaking' under the squeegee in isolated high spots of the pavement being sealed. Generally, the larger the aggregate, that is, the coarser the texture of the cured surface, the greater the skid resistance. Within the sealer industry, the gradations used generally vary within the limits given in Table 2.1.

Table 2.1 Range of Gradations Used In Typical Coal-Tar Mixtures		
Sieve Size	Percent Passing by Total Weight	
	Typical Coarse Gradation	Typical Fine Gradation
1.18 mm (No. 16)	100	--
600 μm (No. 30)	25-85	100
300 μm (No. 50)	2-10	35-75
150 μm (No. 100)	0-2	2-10
75 μm (No. 200)	--	0-2

The amount or quantity of aggregate added to the mixture is limited by the ability of the sealer mixture to hold the aggregate in suspension. Generally, the

smaller the average particle size, the greater the quantity of aggregate that can be successfully suspended in the mixture. Most mixtures containing coal tar and some additional water will contain 0.36 to 0.75 kg (3 to 6 lb) of aggregate per liter (gal) of coal tar emulsion. Coal tar sealers with less than a 0.24 kg (2 lb) 'loading' of aggregate may not provide satisfactory skid resistance. Aggregate quantities greater than 0.75 kg (6 lb) per liter (gal) of emulsion can only be applied through the use of a polymer additive.

Laboratory analysis has shown that, as the amount of aggregate is increased, the fuel resistance of the cured surface will decrease. The fuel resistance of coal-tar mixtures is normally measured by a procedure currently specified in ASTM D 2939 (ASTMb 1999). Generally, sealers with aggregate quantities greater than about 0.75 kg (6 lb) of aggregate per liter (gal) of coal tar emulsion have failed this test (Shook et al. 1990).

Polymer materials usually provide an increased viscosity to the coal tar sealer mixture thereby allowing for increased aggregate suspension. Polymer additives also provide the following advantages: the sealer cures quicker - which is helpful in cooler weather, tracks less - which is helpful in warmer weather, and helps prevent the aggregate from raveling. Most polymer materials are added during the field mixing process. The polymer types used include: acrylonitrile-butadiene, styrene-butadiene, acrylics, and epoxies. Currently, acrylonitrile-butadiene is the polymer used in over 90 percent of all applications. Several emulsion manufacturers produce emulsions that have been polymer modified prior to emulsification. These are marketed as being superior in performance to those coal tar emulsions modified with polymer additives

in the field. These products are more expensive and currently constitute less than 5 percent of the sealer market.

Table 2.2 provides a range of material quantities often specified for coal-tar sealer mixtures. The material quantities given are based on a given amount of coal-tar emulsion in the mixture, generally per 100 liters (gal). A topcoat application of plain coal-tar emulsion (no aggregate) is generally used when aggregate quantities exceed about 0.75 kg (6 lb) of aggregate per liter (gal) of coal tar emulsion.

Table 2.2 Range of Quantities and Application Rates of Coal-Tar Sealer Materials					
Coating	Emulsion ¹ , liter (gal)	Water ¹ , liter (gal)	Aggregate ¹ , kg (lb)	Polymer ¹ , liter (gal)	Application Rate liter/sq m (gal/sq yd)
Standard	100	20-80	90-725 (200-1600)	2-10	0.68-2.25 (0.15-0.5)
Top Plain	100	50-80	0	3-4	0.68-0.9 (0.15-0.2)
¹ Quantities of water, aggregate, and polymer are based on a set amount of emulsion.					

CONSTRUCTION PRACTICES

The following paragraphs detail the basic practices used, some may be eliminated if not required by existing pavement conditions.

Pavement Preparation

The pavement should be structurally sound throughout; distressed areas should be repaired with new asphalt concrete. Pavement areas that have been previously exposed to aliphatic type solvent spills will require either cleaning and priming or removal and repair prior to sealing. The action required will depend on the severity and length of time since the spill. The pavement should be evaluated during hot weather, if the surface is sound, surface particles will be difficult to remove, and then

it can be cleaned and primed. If surface particles are easily removed, then the damaged pavement should be removed, down to sound pavement, and replaced with new asphalt concrete. There are several methods to clean a pavement surface. These include removing material with absorptive compounds, dry scraping, scrubbing with an industrial soap or degreaser, or scarifying (Camillo 1991 and Ralph 1996). These methods should be attempted in the order listed. Another method that is sometimes proposed, using propane torches to burn away oil or grease deposits, should not be used as it will damage the pavement which eventually will require replacement (Ralph 1996). In some instances high-pressure water can be used to clean the pavement surface. After the areas have been cleaned, a primer should be applied. The primer prevents aliphatic solvents from moving up out of the pavement and into the sealer, thereby causing softening, cracking, or debonding of the sealer. Currently, commercial available primers are usually latex emulsion products. In the past, solvent-based materials such as varnish and shellac were often used. A light application of 200- to 300- μm (50- to 70-mesh) aggregate is often sprinkled on top of the primer to promote better bond between the primer and the seal coat (Camillo 1991). Whatever surface preparation is required, prior to applying the sealer, the area should be swept and, if necessary, rinsed with water to remove all unwanted materials.

When coal tar sealers are to be applied to new asphalt concrete pavement or to areas that have been recently repaired, the new pavement surface must be allowed to cure prior to placement. If the pavement is not properly cured, there can be a problem of compatibility between the asphalt and the coal tar. This incompatibility evolves from excess volatiles in the new asphalt concrete and coal tar sealer. An old,

weathered asphalt surface will benefit from the absorption of the coal tar volatiles; however, an application of coal tar sealer to a new asphalt concrete surface seals in the volatiles from both materials which can soften and weaken the asphalt concrete surface and lead to bonding problems (Cobb and Krishon 1986 and Krishon 1987). The length of cure time required before the application of a coal tar sealer depends on the existing weather conditions and the surface condition and amount of asphalt cement in the pavement. Considering these variables, new pavement surfaces should generally cure for from 2 to 6 months before application of a coal tar sealer (Cobb and Krishon 1986).

Old, dry, open-textured asphalt concrete pavements will tend to absorb more of the liquid components of the coal tar sealer. This type of surface will usually benefit from the application of a prime coat prior to the application of the coal tar sealer. The prime coat normally consists of a spray application of coal tar emulsion diluted with 1 to 2 parts water. When a prime coat is not applied to this type of surface additional water (5 to 10 percent) must be added to the sealer mixture. This will allow for the increased absorption of moisture and allow for complete wetting or filling all voids in the pavement surface and achieving complete bonding to the pavement.

Application

After the pavement has been properly prepared, the coal tar sealer mixture can be applied either through spraying or by squeegee. Coal tar sealers are normally placed in at least two coats. Two coatings are desired because coal-tar sealer mixtures often form *holidays* (small air pockets) as they cure and dry. The use of two coatings provides greater assurance of achieving a complete seal. When possible these coatings should be placed perpendicular to each other to assure complete coverage. There are

three types of application methods: (1) hand squeegee, (2) mechanical squeegee, and (3) mechanical spray. Hand squeegees can be used on small jobs or for areas not suitable to mechanical methods. They provide good control, low overhead, and good application on varied surfaces. Mechanical squeegees are widely used and provide high application rates and can fill in small cracks and other imperfections in the surface. Mechanical spraying also provides high application rates and works best on newer or smoother textured pavements. Therefore, spraying can be an effective method of applying a second layer of sealer. Spray wands may be used to apply sealer in hard to reach locations. High wind conditions may prevent or hamper satisfactory spray applications. A nylon brush broom can be effective in applying sealer along edges, such as curbing, sidewalk, or grass.

The rate of application, especially for squeegee-applied mixtures is controlled by the condition of the asphalt surface to be sealed and the amount and maximum particle size of the aggregate in the mixture. The amount of sealer mixture required would generally be greater for asphalt pavement surfaces with surface voids, which commonly increase as pavements age. As the amount and particle size of the aggregate increase, the required rate of application will also increase. Table 2.2 provides a general range of application rates commonly used with various mixtures. All manufacturers recommend a minimum of two coatings of coal-tar sealer.

Coal tar sealers, unlike asphalt slurry seals, are mixed and placed as batches and not on a continuous mix basis. The batches are based on a volume of emulsion with designed volume of water and additive (if used) and by weight of aggregate. In the field the materials are added to the batch mixer in the following order: emulsion,

water, additive (if used), and aggregate. When a polymer additive is used, it is usually diluted with water by a minimum of 100 percent to allow for more complete mixing with the coal-tar emulsion.

The minimum temperature usually allowed for application is 10°C (50°F). Generally, warmer temperatures are better for application. Placement should not occur if rain or freezing temperatures are anticipated prior to complete cure of the sealer. On very hot sunny days, a water fog spray should be applied to the pavement prior to application.

Curing

The time required for a coal tar sealer to cure is controlled by the existing weather conditions. The time required for the water contained in the coal tar emulsion and any additional water added to the mixture to evaporate can be considered as the cure time. This will normally range from 4 to 24 hours depending on the mixture proportions and weather conditions. A sealer can be judged as cured, when the construction distributor truck or an anticipated type of traffic vehicles can traffic the sealed surface without causing displacement or other damage to the seal.

RHEOLOGICAL PROPERTIES

An inherent characteristic of most engineering materials is deformation or flow under an externally applied load. Rheology is the study of the flow process or the science of deformation and it deals with the relationships between stress and strain and their time-dependent derivatives. Newton is credited with observing that the shear stress/strain ratio in a liquid was proportional to the shear strain rate. This holds true for a Newtonian liquid; however, most liquids exhibit non-Newtonian behavior, that is, a nonlinear ratio of shearing stress to shearing strain. Viscosity can be described as

the resistance to deformation, or the internal friction of a liquid, represented by the ratio of the shearing stress to the shearing rate. This ratio or viscosity is also called the coefficient of viscosity. Considering the ratio, the steeper the slope of the plotted results or greater values of stress to strain indicate a higher viscosity or more viscous fluid (RRL 1962). Actual engineering materials exhibit a great variety and complexity of behavior. Idealistically, the behavior of most materials can be simplified and classified into elastic, plastic, and viscoelastic behavior, Figure 2.1.

Elastic Behavior

A material exhibiting elastic behavior requires that upon loading an immediate elastic strain be obtained, which is directly proportional to stress, Figure 2.1. When the stress is applied at a fixed rate, the strain will remain constant and obtain full recovery when the load is removed. A defining characteristic of elastic strain is that it is completely recoverable. Most engineering materials behave elastically or nearly so, provided the stress levels remain small.

Plastic Behavior

At higher stress levels most materials no longer exhibit elastic behavior. The stress limit at which the behavior is no longer elastic is called the elastic limit. Stresses above this limit cause a permanent or inelastic strain, meaning that the strain does not fully recover after removal of the stress. In some materials, the strain, under a constant load, continues to increase for a short time before becoming constant. The permanent strain is called plastic strain, Figure 2.1. Plastic strain is generally time-independent, although some time-dependent strain is often observed accompanying plastic strain.

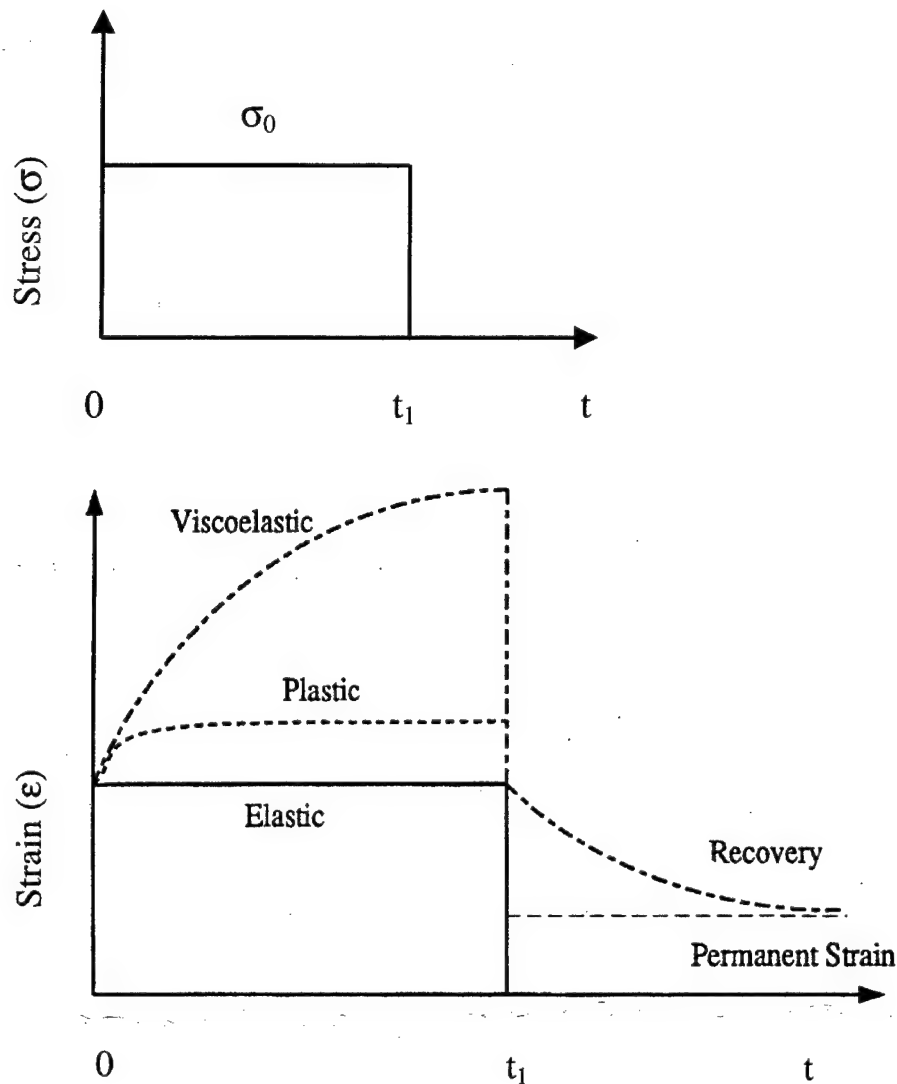


Figure 2.1 Various strain responses to constant load and unload conditions.

Viscoelastic Behavior

A viscoelastic material exhibits some elastic action upon loading (if the loading is rapid enough) and thereafter exhibits slow and continuously increasing amounts of strain at a decreasing rate, Figure 2.1. When the load is removed there is an initial elastic recovery (rapid) following a continuously decreasing strain. The stress response will be out of phase (delayed) when compared to the strain. Typically,

the longer the time to reach the final (lower) value of stress, the larger the corresponding strain. As the name implies, viscoelasticity combines viscosity (viscous flow) and elasticity. Since time is a very important factor in viscoelastic material behavior, they can also be called time-dependent materials. The behavior of most viscoelastic materials is also affected by temperature conditions. Test methods to determine the material property values of a viscoelastic material need to consider these factors of time and rate of loading and temperature.

Linear and Nonlinear Behavior

Materials exhibit linear behavior if stress is proportional to strain at any given time. Therefore, a material is nonlinear when an applied stress doesn't result in a proportional strain. Classical *small-strain theory* holds that materials behave linearly at small strain levels, usually less than one percent. Most materials are nearly linear over certain ranges of stress, strain, time, and temperature. They are nonlinear over larger ranges of these variables (Findley et al. 1976). Many materials behave linearly at greater stress levels if the duration of loading is short, while linearity at longer periods of loading requires lower stress levels. Extremely short loading times, such as the loading from a fast moving vehicle, need a dynamic type of test method. Longer loading times are generally best represented by stress-relaxation test methods (Findley 1976). The actual demarcation of a boundary between linear and nonlinear behavior is somewhat arbitrary and must be investigated through testing. The use of linear constitutive equations or models will yield acceptable results only when the material properties are obtained within the range of linear behavior. The further the test results are obtained from a region of linearity, the poorer will be the approximation of the actual material behavior. The ability to evaluate materials within the linearity region

behavior results in the elimination of the greater complexity required for analysis within the nonlinearity region of behavior. The properties obtained in the linear region can often be used as a satisfactory method of evaluating materials without the excessive complexity of nonlinearity behavior.

LINEAR VISCOELASTIC MODELS

The behavior of viscoelastic materials under an axial stress can be represented by various combinations of two basic mechanical elements. These elements are linear springs (Hookean springs) and linear viscous dashpots (Newtonian dashpots). In the linear spring, shown in Figure 2.2 (a), stress, σ , is related to the strain, ϵ , as shown in Equation 2.1.

$$\sigma = E\epsilon \quad (2.1)$$

where E , is known as the proportionality constant, a linear spring constant, or Young's Modulus. In this equation the stress is linearly proportional to the strain. The spring element exhibits instantaneous elasticity (no oscillations) and instantaneous recovery. Only a purely elastic solid would perform in this manner and so therefore the spring does not adequately model most materials, especially viscoelastic materials.

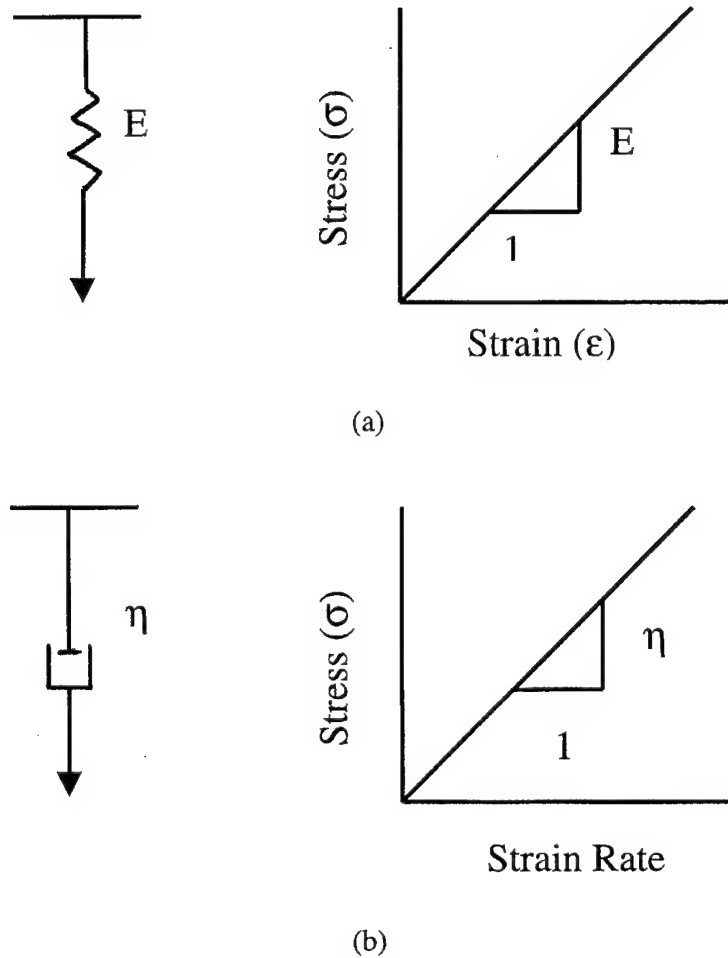
The time-dependency property of viscoelastic materials can be modeled with a linear dashpot. Newton's law, Equation 2.2, is the equation of motion for a model with a simple linear viscous behavior.

$$\sigma = \eta \frac{d\epsilon}{dt} \quad (2.2)$$

where

σ = stress

η = viscosity



**Figure 2.2 Schematic representation of basic elements
(a) Spring, (b) Dashpot.**

$$\frac{d\varepsilon}{dt} = \text{partial derivative of strain with respect to time}$$

The mechanical analogue of Equation 2.2 is the dashpot; see Figure 2.2 (b). The dashpot acts as a piston in a cylinder filled with a liquid of viscosity η . The dashpot will deform continuously at a constant rate when subjected to a constant stress.

Materials whose stress is proportional to the strain rate are called viscous materials.

As with the spring, a dashpot by itself doesn't provide a good quantitative description of material response.

The limitations of the spring and dashpot elements can be overcome by using them in various combinations to achieve the desired response. In the following section these basic elements are combined to produce a model with the desired response.

Maxwell Model

The simplest combination of the viscous and elastic elements is the Maxwell model in which the spring and the dashpot are connected in series as shown in Figure 2.3. The Maxwell element represents a material with elasto-viscous behavior since it is a viscous fluid with elastic properties. All viscoelastic materials are intermediate between elastic solid and viscous liquid (Ferry 1961). Both the spring and the dashpot are subjected to the same stress but are not permitted independent strains. In the Maxwell element, since both elements are connected in series, the total strain, ε , is the sum of the strain in the spring (elastic strain) plus the strain in the dashpot (viscous strain), as given in Equation 2.3.

$$\varepsilon = \varepsilon_1 + \varepsilon_2 \quad (2.3)$$

In this element, E , the instantaneous tensile modulus, characterizes the response of a spring while, η , the viscosity of the liquid in the dashpot, defines the viscous behavior. The stress-strain relationship of the two-element model for the spring and dashpot is given in Equations 2.4 and 2.5, respectively.

$$\sigma = E\varepsilon_2 \quad (2.4)$$

$$\sigma = \eta\dot{\varepsilon}_1 \quad (2.5)$$

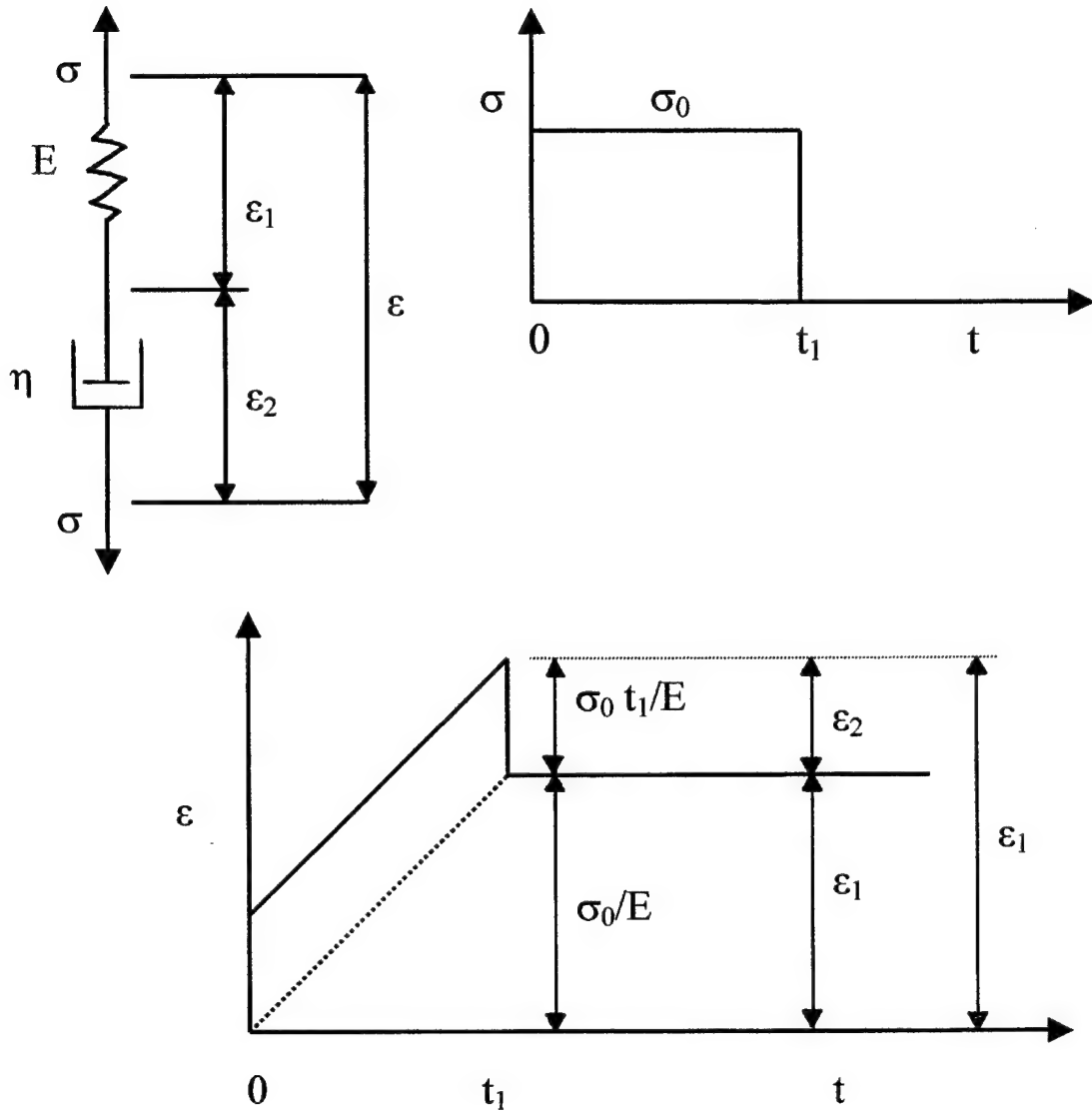


Figure 2.3 Behavior of the Maxwell Model.

These equations are similar to Equations 2.1 and 2.2, except for ϵ_2 = the strain in the spring and $\dot{\epsilon}_1$ = partial derivative of strain with respect to time. The strain rate is obtained by Equation 2.6.

$$\dot{\epsilon} = \dot{\epsilon}_1 + \dot{\epsilon}_2 \quad (2.6)$$

Examining Equations 2.4, 2.5, and 2.6, the strain-time relationship of the model can be obtained by inserting Equation 2.5 and the time derivative of Equation 2.4 into Equation 2.6. The stress-strain rate for the model is given in Equation 2.7.

$$\dot{\varepsilon} = \frac{\dot{\sigma}}{E} + \frac{\sigma}{\eta} \quad (2.7)$$

Strain-time relations under various stress conditions and stress-time relations under a given strain can be obtained by solving Equation 2.7. From Figure 2.3, the strain-time relation when integrating with the initial conditions of $\sigma = \sigma_0$ at $t = t_0$

$$\varepsilon(t) = \frac{\sigma_0}{E} + \frac{\sigma_0}{\eta} t \quad (2.8)$$

If the stress is removed from the Maxwell model at t_1 , the elastic strain σ_0 in the spring returns to zero at the instant the stress is removed, while $(\sigma_0/\eta) t_1$ represents a permanent strain.

If the Maxwell model is subjected to a constant strain, ε_0 , at time $t = 0$, at an initial stress of σ_0 , the stress response at time t , $\sigma(t)$, can be obtained by integrating Equation 2.7.

$$\sigma(t) = \sigma_0 e^{-Et/\eta} = E\varepsilon_0 e^{-Et/\eta} \quad (2.9)$$

Equation 2.9 describes the effect of stress relaxation for a Maxwell model under constant strain, Figure 2.3. The rate of stress change is given by the derivative of Equation 2.9.

$$\dot{\sigma} = -(\sigma_0 E / \eta) e^{-Et/\eta} \quad (2.10)$$

The initial rate of stress change at $t > 0$ (time just after application of strain), is $\dot{\sigma} = -\sigma_0 E / \eta$. With the stress decreasing continuously at this rate, the relaxation equation takes the following form.

$$\sigma = -(\sigma_0 E / \eta) t + \sigma_0 \quad (2.11)$$

Evaluating Equation 2.11, shows that the stress will reach zero at time $t_R = \eta/E$, which is called the relaxation time of the Maxwell model. The relaxation time, t_R , characterizes one of the viscoelastic properties of the material, Figure 2.3. The majority of the stress relaxation (63 percent) occurs prior to this time (Findley 1976)

The Maxwell model does not completely represent the complex behavior of a viscoelastic material. The model does not include a provision for delayed elasticity common in viscoelastic binder materials. Delayed elasticity is described in the description of the following model.

Kelvin Model

The Kelvin, or Voigt, model combines a Hookean spring and a Newtonian dashpot in parallel, Figure 2.4. The stress-strain relationships for the Kelvin model are represented by Equations 2.12 and 2.13.

$$\sigma_1 = E \epsilon \quad (2.12)$$

$$\sigma_2 = \eta \dot{\epsilon} \quad (2.13)$$

The total stress, σ , as defined in Equation 2.14 is the sum of the stress in each element, as they are connected in parallel.

$$\sigma = \sigma_1 + \sigma_2 \quad (2.14)$$

Substituting Equations 2.12 and 2.13 into 2.14 to eliminate the terms σ_1 and σ_2 yields Equation 2.15.

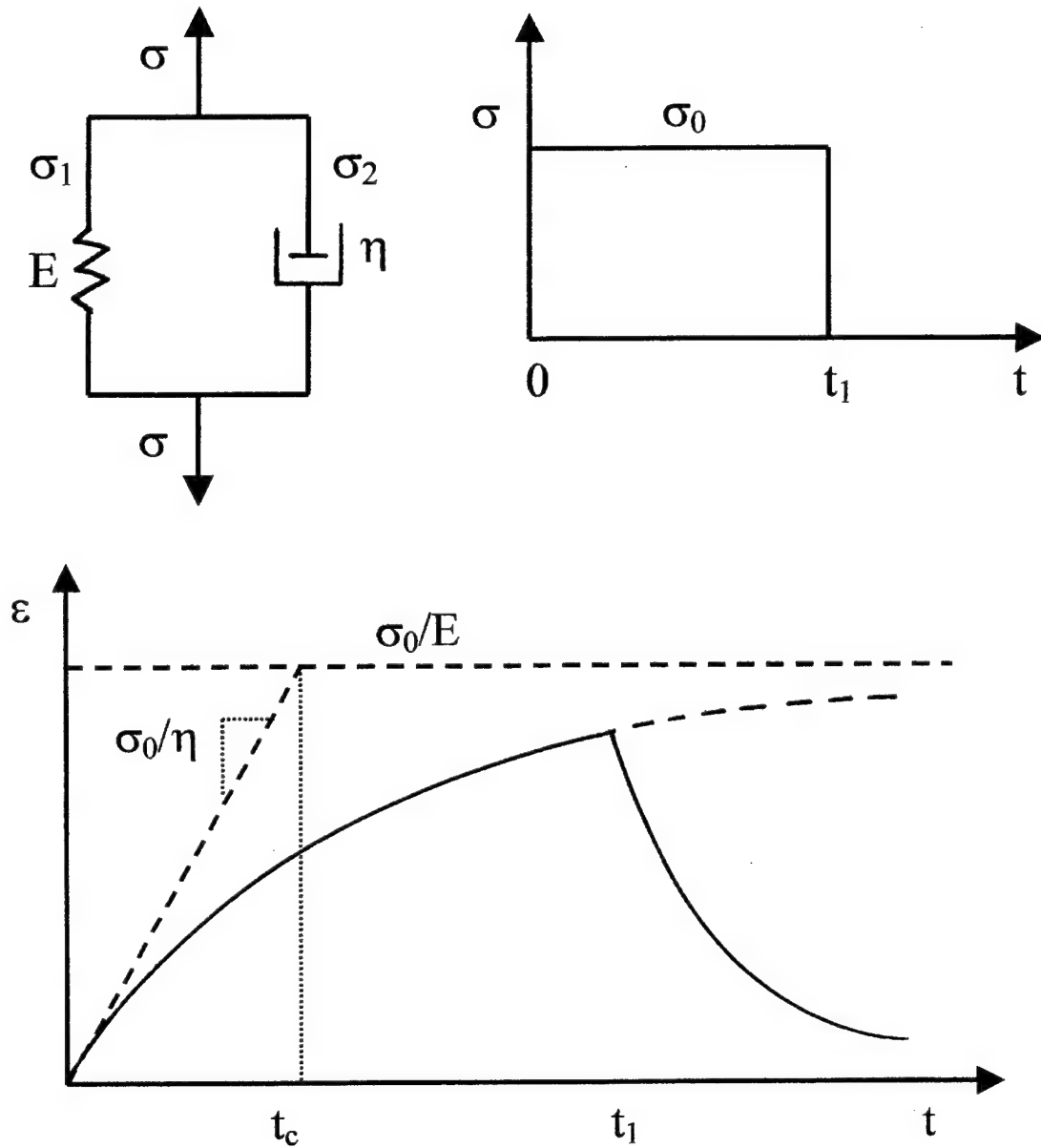


Figure 2.4 Behavior of the Kelvin Model.

$$\dot{\varepsilon} + \frac{E}{\eta} \varepsilon = \frac{\sigma}{\eta} \quad (2.15)$$

The solution to this equation for creep, ε , under a constant stress, σ_0 , applied at time, $t = 0$ has the form given in Equation 2.16 (Findley et al. 1976).

$$\dot{\epsilon} = \frac{\sigma_0}{E} (1 - e^{-Et/\eta}) \quad (2.16)$$

The strain described in Equation 2.16 increases at a decreasing rate with time and approaches asymptotically σ_0/E as t approaches infinity. In this model an abruptly applied stress is initially carried entirely by the dashpot (viscous element, η). This viscous element elongates from the applied stress; thereby, transferring an increasing portion of the load to the spring (elastic element, E). Eventually, the entire stress is carried by the elastic element. This behavior is aptly described as delayed elasticity.

The strain rate for the Kelvin model in creep under a constant stress can be obtained by integrating Equation 2.16, as shown in Equation 2.17.

$$\dot{\epsilon} = \frac{\sigma_0}{\eta} (e^{-Et/\eta}) \quad (2.17)$$

The Kelvin model cannot be used to demonstrate stress relaxation with a constant strain. The presence of a viscous element requires that abrupt changes in strain, σ_0 , could only be accomplished with an infinite stress. Once a level of strain has been achieved, the stress in the viscous element eventually returns to zero and the constant stress is held on the elastic element (spring).

Neither the Maxwell nor the Kelvin models are able to completely represent the behavior of most viscoelastic materials. The following describes the major limitations of each model. The Maxwell model provides no time-dependent recovery and does not show a decreasing strain rate under constant stress (creep). The Kelvin model does not exhibit time-dependent strain on loading or unloading and it does not allow for a permanent strain after unloading (Findley et al. 1976).

Burgers or Four-Element Model

The Burgers or the four-element model is the simplest model that exhibits all the essential features of viscoelasticity (Sperling 1992). The Burgers model is made up of a Maxwell and a Kelvin model connected in series, Figure 2.5. The constitutive

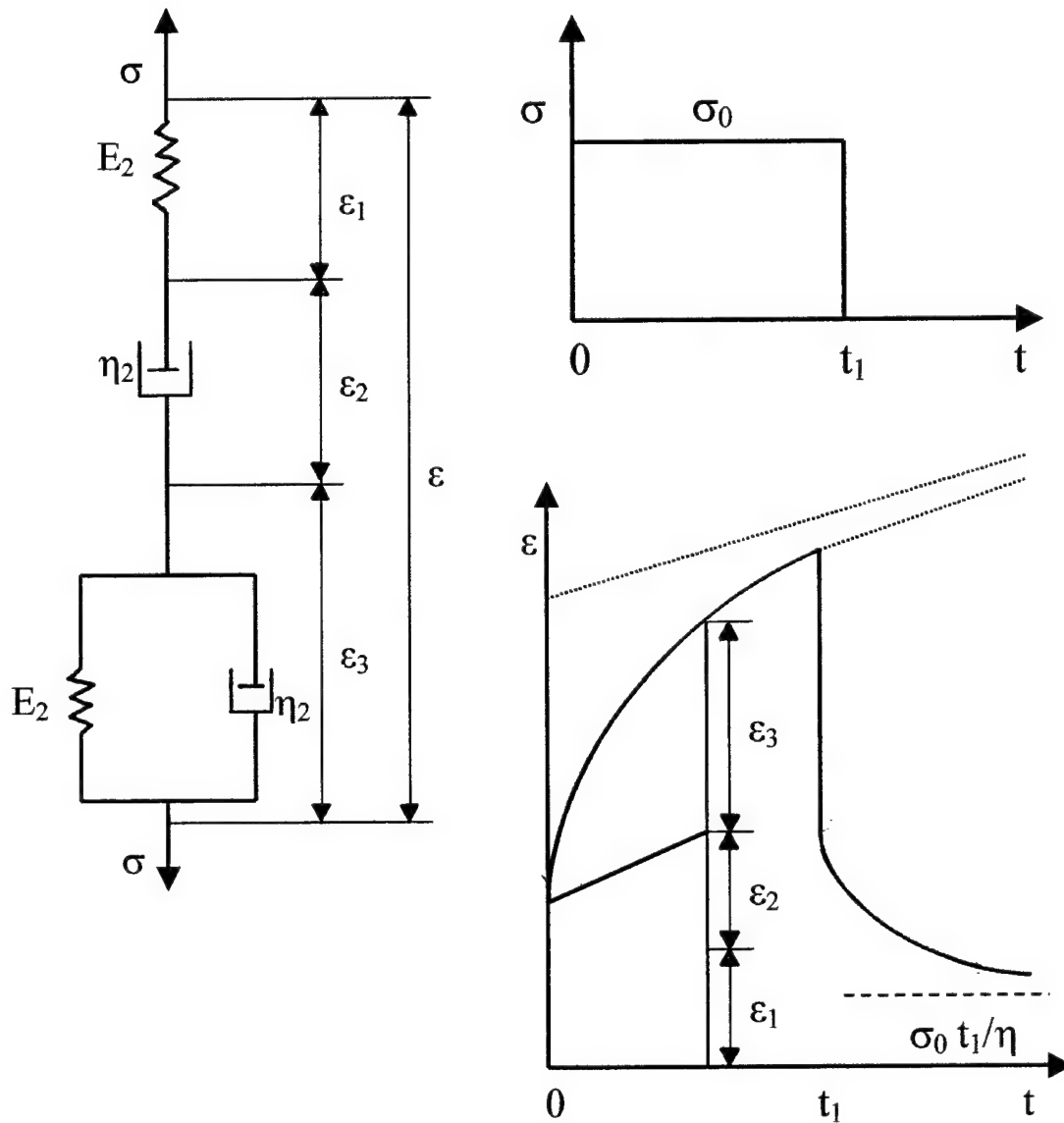


Figure 2.5 Behavior of the Burgers Model.

equation for the model can be developed by considering the strain response of the model under the constant stress of each of the elements. The total strain at time, t , is the sum of the strain in the three elements, the spring and dashpot of the Maxwell model are considered as two elements, as shown in Figure 2.5.

$$\varepsilon = \varepsilon_1 + \varepsilon_2 + \varepsilon_3 \quad (2.18)$$

where ε_1 is the strain in the spring,

$$\varepsilon = \frac{\sigma}{E_1} \quad (2.19)$$

ε_2 is the strain in the dashpot,

$$\dot{\varepsilon}_2 = \frac{\sigma}{\eta_1} \quad (2.20)$$

and ε_3 is the strain in the Kelvin model which can be derived from Equation 6.15

$$\dot{\varepsilon}_3 + \frac{E_3}{\eta_3} \varepsilon_3 = \frac{\sigma}{\eta_3} \quad (2.21)$$

A constitutive equation can be obtained between the stress and strain for the Burgers model. Using Equations 2.18, 2.19, 2.20, and 2.21 and eliminating the internal variables for the individual strains of each element (ε_1 , ε_2 , and ε_3), yields Equation 2.22.

$$\sigma + \left(\frac{\eta_1}{E_1} + \frac{\eta_1}{E_2} + \frac{\eta_2}{E_2} \right) \dot{\sigma} + \left(\frac{\eta_1 \eta_2}{E_1 E_2} \right) \ddot{\sigma} = \eta_1 \dot{\varepsilon} + \left(\frac{\eta_1 \eta_2}{E_2} \right) \ddot{\varepsilon} \quad (2.22)$$

Findley, shows how to obtain Equation 2.22 through the use of Laplace transforms (Findley et al. 1976).

The creep behavior of the Burgers model under a constant stress, σ_0 , obtained from Equation 2.22. This equation is solved with the second order differential equation with the two following conditions:

$$\varepsilon = \varepsilon_1 = \frac{\sigma_0}{E_1}, \varepsilon_2 = \varepsilon_3 = 0, t = 0 \quad (2.23)$$

$$\dot{\varepsilon} = \frac{\sigma_0}{\eta_1} + \frac{\sigma_0}{\eta_2}, t = 0 \quad (2.24)$$

The use of another Laplace transformation for solving differential equations, as given by Findley, determines the creep behavior for the Burgers model as illustrated in Figure 2.5 and given in Equation 2.25.

$$\varepsilon = \frac{\sigma_0}{E_1} + \frac{\sigma_0}{\eta_1} t + \frac{\sigma_0}{E_2} (1 - e^{-E_2 t / \eta_2}) \quad (2.25)$$

A comparison of this equation of creep behavior with the equations for both the Maxwell (Equation 2.8) and the Kelvin (Equation 2.17) models shows that Burgers model is the sum of the other two. In Equation 2.25 the first two terms on the right side represent instantaneous elastic strain and viscous flow, and the last term represents the delayed elasticity of the Kelvin model. This results in a permanent strain value of $(\sigma_0 t_1 / \eta)$.

An equation to define relaxation behavior maybe obtained from Equation 2.22 by applying an instantaneous step of strain of ε_0 at $t = 0+$. Considering the type of loading function and through the use of Laplace transformation an equation for stress relaxation can be developed that considers all the elements of the model (Findley et al. 1976).

SUMMARY

Coal tar emulsions can be used to construct fuel-resistant pavement sealers. There is currently no general agreement, within the sealer industry, concerning a mix design procedure or required material properties. There is a basic agreement concerning construction procedures and the necessity of simple safety provisions. The safety requirement centers on protecting workers from direct skin contact or exposure to vapors.

Coal tar materials, and in particular Road Tar from which coal tar emulsions are manufactured, age and harden mainly by evaporation of volatile components. This would indicate that the aging or hardening could occur faster in areas with higher temperatures.

Coal tar emulsion sealers generally fail by cracking, after a few years of field exposure. This occurs in all types of climates, even where freezing temperatures are never or almost never encountered. Coal-tar emulsions do not flow after curing, even when exposed to high temperatures.

Investigation has shown that coal-tar sealers are widely used to seal airfield pavements. The life expectancy is from 3 to 5 years. Mixtures containing latex (polymer) additives have shown improved field performance over plain coal-tar mixtures. Polymer additives have also been shown to increase mixture viscosity and allow for faster curing. Many test methods and procedures have been developed; however, none of these tests address the basic engineering properties of the materials or consider related field performance.

Coal-tar sealer mixtures will not remain effective fuel-resistant sealers when too much aggregate is added to the mixture. The amount of aggregate at which this occurs depends upon the amount, size, and properties of the aggregate.

Sealers can be placed either with squeegees or by spraying. They should be applied in two coats, with the second coat, if possible, applied perpendicular to the first. The coal-tar emulsion must be allowed 4 to 24 hours to cure prior to applying a second coat or opening the pavement to traffic.

Viscoelastic materials are time and temperature dependent. They exhibit some elastic action upon loading, followed by a continuously increasing strain at a decreasing rate. Stress relaxation under a constant strain is a characteristic of this type of material. The various models were presented to help describe the action of coal-tar mixtures under strain. The four-element (Burgers) model is the simplest capable of accurately depicting a final permanent strain. A stress relaxation test would appear most applicable to represent the type of non-load related thermal movements to which coal tar mixtures are exposed. These thermal movements are not necessarily related to freeze thaw but only to general changes in temperature.

CHAPTER 3: FIELD EVALUATION

INTRODUCTION

A field evaluation was conducted at the Waterways Experiment Station for over two years from November 1997 until the spring of 2000. The evaluation involved the application of various coal-tar sealer mixtures in selected proportions and application rates on a prepared asphalt concrete pavement. These sealer applications were not trafficked but were monitored for performance in regards to the first appearance of cracking or any other type of distress that might occur.

The materials, underlying pavement, and construction practices used in this field evaluation were selected to meet the following criteria:

- The materials must be representative of those generally available and currently used throughout the coal tar sealer industry.
- The material supplier must be willing to provide information and the desired range of products and accept their use in the study.
- The underlying pavement must be typical of Corps of Engineers (CE) airfield pavements.
- The construction practices used would be typical of hand application for small projects or for handwork required when obstacles prevent mechanical application.

MATERIALS

The coal tar emulsion and additive materials used in this study were provided by the manufacturers on a voluntary, no cost basis, together with information and recommendations on mixture design and application. The aggregate used in this study

was obtained from a local supplier. According to the emulsion manufacturers, sealing contractors often use similar sources for their aggregate.

Coal Tar Materials

The coal tar materials used in this study, Table 3.1, were obtained from two separate emulsion manufacturers. The two standard emulsions were obtained as a group or from one production run by each manufacturer (1a – 2a). This means that the emulsion samples all came from the same base RT-12 coal tar and contained the same clay and emulsifying agents and additives. The emulsions were supplied in 19 liter (5 gal) plastic buckets, which facilitated mixing and handling for placement by hand. Manufacturer number 1 also supplied a coal tar emulsion, with high ash content (1b). The ash content of a coal-tar emulsion is determined according to ASTM D 2939 (ASTMb 1999). A high-ash content indicates a coal-tar emulsion containing more than the standard amount of clay. Manufacturer number 1 also supplied a polymer-modified coal-tar emulsion (1c). This material was a coal tar that was combined with a polymer prior to emulsification. Table 3.2 contains the physical properties each of these emulsions, except for the polymer-modified coal-tar emulsion (1c), as determined according to ASTM D 5727 (ASTMa 1999). Neither this ASTM standard nor any others are applicable for evaluating polymer-modified coal-tar emulsions.

Table 3.1 Types of Coal Tar Materials and Additives Obtained from Manufacturers		
Sample Designation	Coal Tar Emulsion (CTE)	Type of Field Additive
1a	Standard Coal Tar Emulsion	Acrylonitrile-Butadiene Latex
1b	High-Ash CTE	
1c	Polymer Mod. CTE	
2a	Standard Coal Tar Emulsion	Acrylonitrile-Butadiene Latex

Additive Materials

The additive materials used in this study are field additives, that is, they are supplied separately from the coal tar emulsion and are combined with it during mixing prior to placement of the sealer material. The additives were supplied by each emulsion manufacturer and are intended for use with their product, Table 3.1. The emulsifying agents and additives used by a manufacturer to produce their coal tar emulsion can be adversely affected by a field additive that is not compatible. The latex additives supplied by each manufacturer were both composed of acrylonitrile-butadiene. These latex (elastomeric) materials were both emulsion-based materials. These latex emulsions contained from 59 to 60 percent water.

Table 3.2 Physical Properties of Coal Tar Emulsion Samples ¹					
Property	Characteristics		Sample ² 1a	Sample ² 1b	Sample ² 2a
	Minimum	Maximum			
Uniformity	No separation that can't be overcome by moderate mixing		Pass	Pass	Pass
Wet Film Cont.	Uniform homogeneous Consistency		Pass	Pass	Pass
Density @ 25°C (77°F), g/mL (lb/gal)	1.2 (10)	--	1.237 (10.31)	1.234 (10.28)	1.223 (10.20)
Residue by Evaporation, %	47	--	53.6 ²	49.5 ²	47.0 ²
Water Content, %	--	53	46.4 ²	50.5 ²	53.0 ²
Resistance to Vol. Wt. Loss, %	--	10	11.4	12.1	12.4
Sol. Of Res. in CS ² , %	20	--	45.3 ²	--	--
¹ Physical properties determined according to ASTM D 5727. ASTM D 5727 is not applicable to polymer-modified coal-tar emulsions.					
² Number and letter designation, as defined in Table 3.1.					

Aggregate

The aggregate used in the coal tar sealer mixtures was silica sand. This sand was a medium-graded sandblasting aggregate, which was purchased in 36 kg (80 lb) bags. Sieve analysis showed that this aggregate contained about 12 percent retained on the 1.18 mm (No. 16) sieve. The aggregate was screened over the 1.18 mm (No. 16) sieve to remove all this sized material and the remaining aggregate was of the gradation shown in Table 3.3. This sand was close to the gradation typically specified in Corps of Engineers (CE) and other federal agency specifications. According to the emulsion manufacturers contacted for this study, the gradation given in Table 3.3 is used only by the agencies mentioned. The vast majority of coal tar seal coats placed use smaller sized aggregate particles. The industry as a whole seems to prefer gradations centered on either the 600 to 425 μm (No. 30 to No. 40) or the 300 to 200 μm (No. 50 to No. 70) sieves.

Table 3.3 Gradation of Aggregate Used for Coal Tar Mixtures		
Sieve Size	Percent Passing by Total Weight	
	Typical CE Gradation	Gradation Used in Mixtures
1.18 mm (No. 16)	100	100
850 μm (No. 20)	--	86
600 μm (No. 30)	25-85	58
425 μm (No. 40)	--	33
300 μm (No. 50)	2-10	11
180 μm (No. 80)	--	1
150 μm (No. 100)	0-2	1
75 μm (No. 200)	--	0

FIELD EVALUATION SECTION LAYOUT

A total of 18 different coal tar sealer mixtures were placed in the field evaluation section. Figure 3.1 provides an overall layout of the section including the

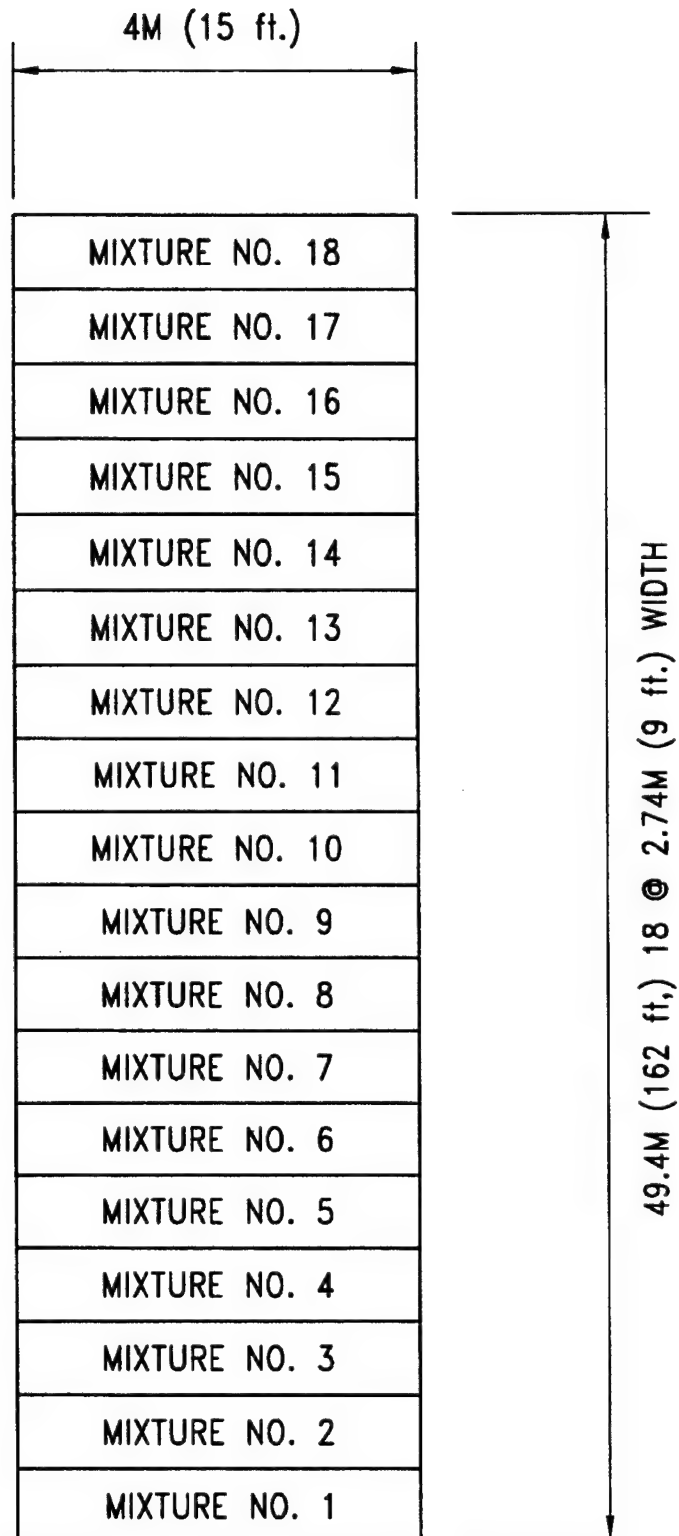


Figure 3.1 Layout of section and location of each mixture.

location of each mixture. The mixtures were placed in three coatings, with each successive coating decreasing in area from 12.5, to 11.3, and 2.9 m² (135, to 121.5, and 31.5 ft²), for each mixture, Figure 3.2. This allowed for an evaluation of the effect of sealer thickness on the performance.

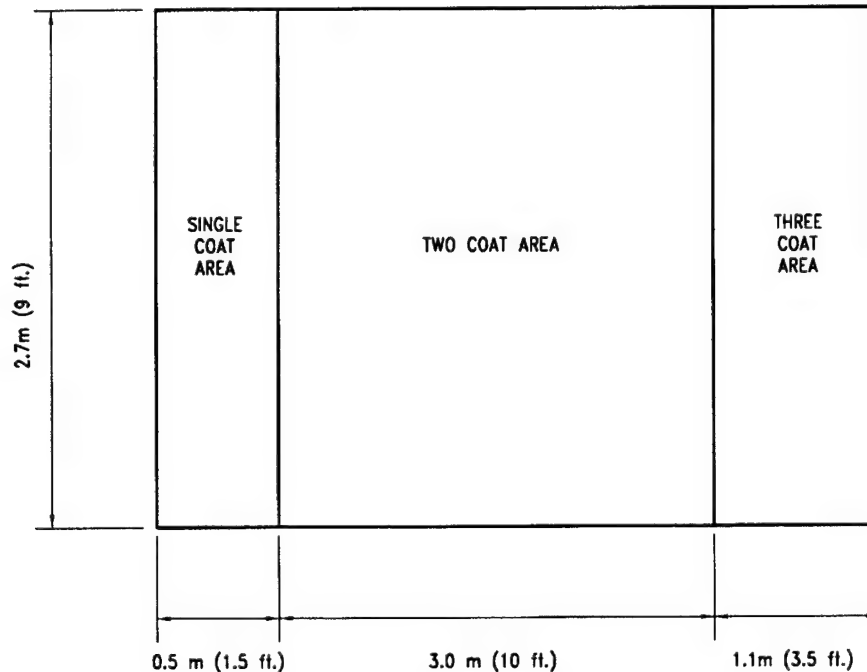


Figure 3.2 Layout of coatings for each mixture.

The sealer materials for this field evaluation were placed on an airfield type hot-mix asphalt pavement, see Figure 3.3. This pavement had been placed during the summer of 1993, and designed around the FAA's Item P 401 guide specification (Plant Mix Bituminous Pavements). The aggregate used for this pavement was crushed limestone (19 mm (3/4 in.) maximum size) and it also contained 15 percent natural sand by total weight of aggregates. AC-30 asphalt cement was used as the



Figure 3.3 Overall view of area prior to application of sealers.

binder. Table 3.4 contains the mixture and field properties determined for this hot-mix asphalt pavement during and immediately after placement.

The pavement at the time of sealing was in excellent condition. It contained no visible construction joints, cracks, or other surface defects, except for several localized low spots along the edges of the section.

MIXTURES

A total of 18 mixtures were placed in the coal tar sealer evaluation section, as shown in Table 3.5. Mixtures 1 through 12 contained coal tar emulsions from one manufacturer. Mixtures 13 through 18 contained coal tar emulsions from the second manufacturer. All sections were placed with three coats, with a minimum of 24-hour curing between coats. Mixes 7 through 10 contain coal tar with high ash content.

Table 3.4 Mixture and Field Properties of Existing Hot-Mix Asphalt Pavement	
Property	Field Sample ¹
Gradation - % Passing	
19 mm (3/4 in)	100
12.5 mm (1/2 in)	91.3
9.5 mm (3/8 in)	78.9
4.75 mm (No. 4)	54.7
2.36 mm (No. 8)	35.5
1.18 mm (No. 16)	26.9
600 µm (No. 30)	22.3
300 µm (No. 50)	11.1
150 µm (No. 100)	8.3
75 µm (No. 200)	7.3
Percent Asphalt	4.7
Stability (Marshall), kN (lb)	8.3 (1867)
Flow, 0.25 mm (0.01 in)	13.4
Percent Voids Total Mix	2.0
Percent Voids Filled	85.4
Laboratory Specific Density	2.471
Max. Theoretical Specific Density - D 2041	2.518
Percentage of Laboratory Specific Density	95.4 ²
¹ Average of two field samples.	
² Average of six field cores.	

Mixes 11 and 12 contain a modified coal tar emulsion. The remaining mixes contained conventional coal tar emulsions.

CONSTRUCTION

The coal tar sealers were placed between 10/29/97 and 12/1/97. The majority of the placement was completed by 11/4/97. Unseasonably cold weather and delays in obtaining a latex additive from one manufacturer extended the time required for placement. The following climatic condition requirements were established for placement of the emulsions:

Table 3.5 Field Test Section Mixture Proportions and Application Rates						
Mix No.	Manufacturer Material Designation	Coal Tar ¹ Emulsion	Water ^{1,2,3}	Additive ¹	Aggregate Kg/liter (#/gal) of Coal Tar	Application Rate ² liters/m ² (gal/yd ²)
1	1a – Standard Emulsion	100	30, 20	---	480 (4)	1.36, 1.13 (.3, .25)
2 ⁴		100	30, 20	---	1,200 (10)	1.36, 1.13 (.3, .25)
3		100	30, 35	3	480 (4)	1.36, 1.27 (.3, .28)
4		100	30, 35	3	1,200 (10)	1.36, 1.27 (.3, .28)
5		100	30, 50	7	480 (4)	1.36, 1.45 (.3, .32)
6		100	30, 50	7	1,200 (10)	1.36, 1.45 (.3, .32)
7	1b – High-Ash Emulsion	100	30, 20	---	480 (4)	1.36, 1.13 (.3, .25)
8		100	30, 20	---	1,200 (10)	1.36, 1.13 (.3, .25)
9		100	30, 35	3	480 (4)	1.36, 1.27 (.3, .28)
10		100	30, 35	3	1,200 (10)	1.36, 1.27 (.3, .28)
11	1c – Polymer Mod. Emul.	100	5	N/A	480 (4)	1.36 (.3)
12		100	5	N/A	1,200 (10)	1.36 (.3)
13	2a – Standard Emulsion	100	30, 20	---	480 (4)	1.36, 1.13 (.3, .25)
14		100	30, 20	---	1,200 (10)	1.36, 1.13 (.3, .25)
15		100	30, 35	3	480 (4)	1.36, 1.27 (.3, .28)
16		100	30, 35	3	1,200 (10)	1.36, 1.27 (.3, .28)
17		100	30, 50	7	480 (4)	1.36, 1.45 (.3, .32)
18		100	30, 50	7	1,200 (10)	1.36, 1.45 (.3, .32)

¹ Liquid components are given based on 100 liters or gallons of coal tar emulsion.

² The first number refers to amounts used for the first coating, the second number refers to the amounts used for the second and third coatings.

³ The percentage of water reported includes the water available from the latex additive, as well as the water added directly, but does not include the water available from the coal tar emulsion itself.

⁴ The third coating of this section incorrectly used mixture number 14.

- Minimum air temperature of 10°C (50°F) and rising,
- The pavement surface contained no ponded water,
- No rain was forecast for at least 24 hours, and
- Freezing temperatures were not expected for at least 24 hours.

For the second and third coating the application rate of sealer material was adjusted and the amount of water increased to allow for better mixing and application. The coal tar and aggregate contents remained constant for all mixtures.

Surface Preparation

The surface of the existing pavement was swept and cleaned with pressurized water, see Figure 3.4. When the air temperature exceeded 21 °C (70°F) and the sun was shining the pavement surface was lightly wetted with water. This was done to prevent the warm pavement from drying the seal coat too fast and possible interfering with placement or bonding with the existing pavement. This was most important because of the relative increase in stiffness of the mixtures with larger amounts of polymer additive and aggregate. A total of eighteen areas were then laid out prior to placing the different mixtures.



Figure 3.4 Typical surface condition of pavement prior to sealing.

Mixing

Materials for each mixture were combined by weight. The specific gravity of the coal tar emulsions was assumed to be 1.2, which was close to the actual value for each emulsion (Table 3.2). The specific gravity of the polymer additives was about 1.0, based on information supplied by the manufacturers. It is standard practice in the sealer industry to base the amount of all mixture constituents on the volume of coal tar emulsion in the mixture.

The components were mixed in a container of suitable volume with an electric drill with a mixing blade attachment, see Figure 3.5. The following blending procedure was used for all mixtures. The coal tar emulsion was added first, followed by water, next the polymer was added (if used), and last, the aggregate, see Figure 3.6. The mixtures were thoroughly mixed during each of these stages and the final mixture was mixed until it was uniform in appearance, see Figure 3.7. The mixtures were then carried and dumped in the area where they were to be placed. The proportioning and mixing of the materials took from 20 to 30 minutes.

Placement

The mixtures were placed by hand with rubber bladed squeegees, see Figure 3.8. The mixtures were spread over the defined area and excess material was worked around until a uniform application was achieved, see Figure 3.9. Initially, squeegees 0.6 m (2 ft) and 1.2 m (4 ft) wide were used; however, experience showed that the small squeegees were better for placing the different mixtures. The smaller squeegees were easier to handle for better control of the depth of placement of the mixture and the slight undulations of the existing pavement posed fewer problems. Mixtures 1, 7, and 13, with no additive and a low amount of aggregate, were the most

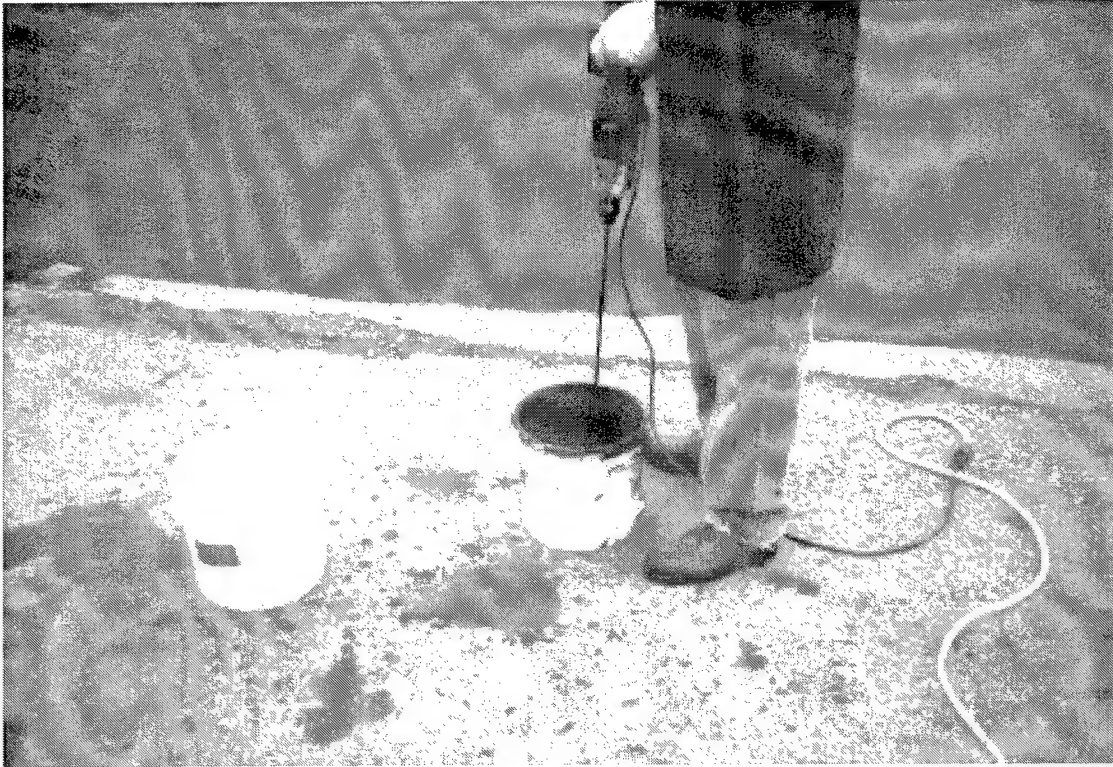


Figure 3.5 Mixing sealer materials with an electric drill and blade mixer.



Figure 3.6 Adding sand mixture to the sealer mixture.



Figure 3.7 Mixing sealer components to a uniform consistency.

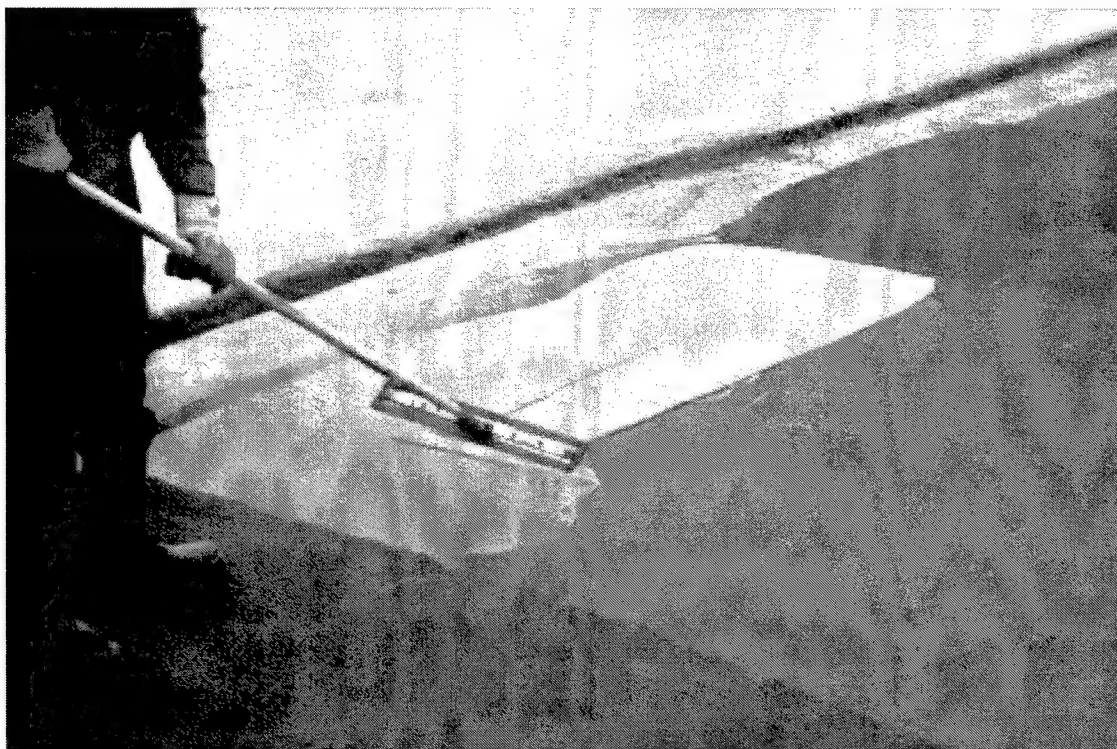


Figure 3.8 Applying sealer mixture with a hand squeegee.

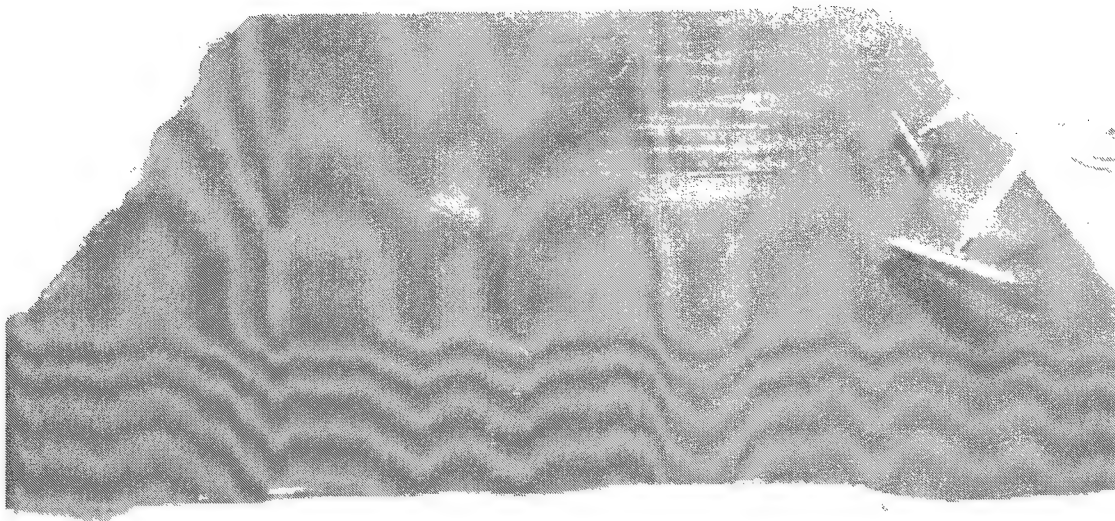


Figure 3.9 Spreading of sealer within a predefined area.

viscous. These mixtures were the most difficult to spread at the desired rate of application during the first coating. The mixtures were placed by odd numbers first followed later or the next day by the even numbered mixtures. This spacing allowed personnel to walk along the entire edge of any area during placement, see Figure 3.10. The second and third coatings were placed in a similar manner. The squeegeeing of each mixture usually took from 10 to 15 minutes.

CORRESPONDING FIELD MIXTURE SAMPLES

Sample Preparation

Initially samples for weathering and later evaluation were to be fabricated during placement of the field section, using portions of the material that was placed on the pavement. Difficulties in material handling, obtaining proper work areas, and limits on molds, resulted in the samples being fabricated in the laboratory at the



Figure 3.10 Applying sealer in alternating locations.

mixture from adhering to the bottom of the mold, a sheet of polyethylene was placed on the bottom of the mold. Prior to placing the mixture into the mold, a silicone release agent was sprayed in the sheeting and the exposed Plexiglas was covered with a light layer of grease to assist in cleaning of the molds after the cured samples were removed from the molds, see Figure 3.11. The mixtures were spread or cast in the molds to a uniform thickness through the use of a plastic straightedge.

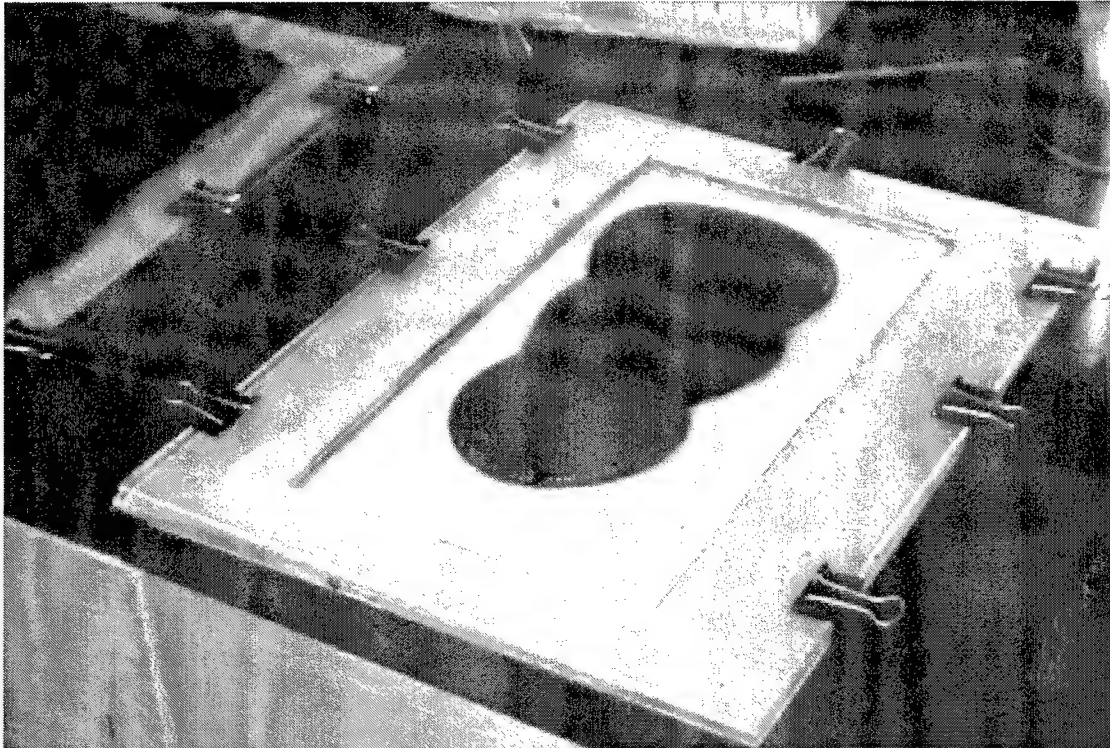


Figure 3.11 Sealer mixture in mold, prior to spreading.

The final size and thickness of the samples depended on the amount of solids and moisture in the mixture. Therefore, the samples with larger amounts of aggregate were thicker. Because of mixing and placing requirements, mixtures with a polymer additive or increasing amounts of additive were usually thinner. The addition of increasing amounts of polymer required increasing amounts of water for mixing and application.

Field Exposure

The formed samples were allowed to cure for from 2 to 3 weeks in the laboratory prior to being placed outside and exposed to local climatic conditions. This was done because of the occurrence of freezing temperatures on some nights and the need to be sure that the weight of the samples had sufficiently stabilized due to water

loss. This was accomplished by assuring that the percent weight loss in the samples prior to placement out in the weather was less than 1 percent, see Table 3.6. The complete samples were placed on top of a structure, less than 800 m (0.5 mile) from the field section. They were placed in metal wire baskets, which allowed air to circulate around each sample, see Figure 3.12. They were positioned so that they received approximately the same amount of sunlight. The samples were turned over approximately every three months to allow each side to receive exposure to sunlight.

Table 3.6 Weight Loss of Various Mixture Samples Over Time					
Sample No.	Original Weight ¹ (gms)	Percent Weight Loss in Percent at Various Times in Days After Casting of Sample			
		7	14	21	6 to 8 Months
1	511.1	0.20	0.19	0.04	—
2	686.1	0.09	0.06	0.01	—
3	432.7	0.37	0.25	0.09	—
4	388.2	0.36	0.28	0.10	—
5	367.2	0.44	0.30	0.08	1.20
6	510.5	0.24	0.22	0.08	0.85
13	527.6	0.40	0.16	0.08	—
14	632.6	0.05	0.05	0.03	0.87
15	371.1	0.11	0.08	0.08	—
16	444.6	0.31	0.02	—	0.73
17	330.6	0.45	0.18	—	1.19
18	479.0	0.23	0.10	—	0.84
Note: 1 - Original weight taken approximately two days after casting.					

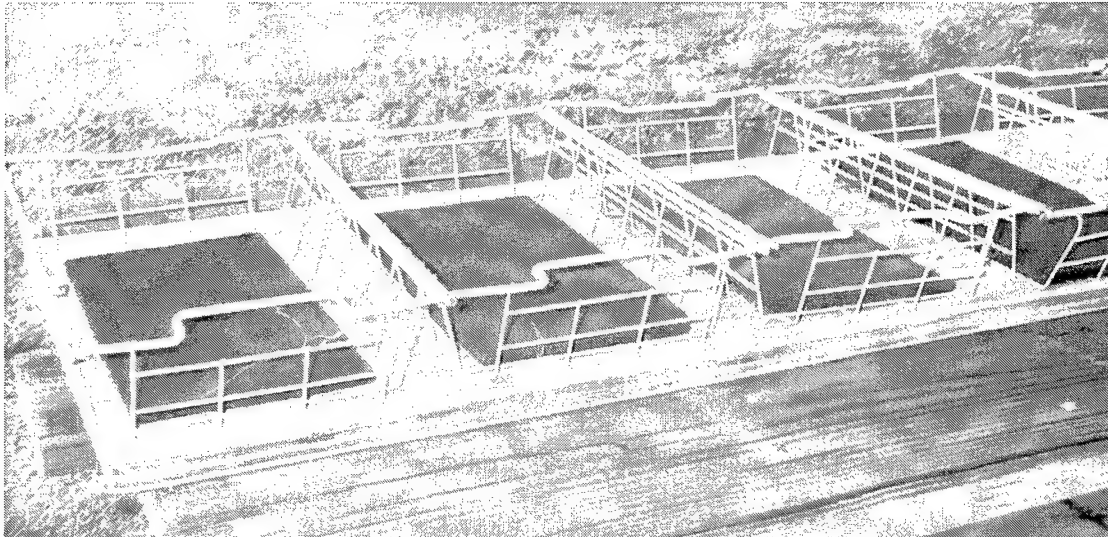


Figure 3.12 Field samples curing in wire baskets.

FIELD EVALUATION SECTION MONITORING

Visual

The field section was visually monitored for any distress that might occur. The only distress that appeared immediately after placement occurred as small crescent shaped tears in about 20 percent of the surface area of Mixture 17. Monitoring was done approximately every two weeks for several months. The rate of inspection was increased to at least once every week after about five months and continued until all the mixtures had cracked. Figure 3.13 shows a typical surface condition of mixture 6, four months after placement.

Cracking usually began with relatively small width, disconnected cracks, which in most sections, would widen and run together with time. The first cracks observed in the field section occurred in mixtures 9, 13, and 15. Cracks were observed in the two- and three-coating areas, except for mixture 9, which had cracks in only the two-coating area. Table 3.7, lists the field section mixture numbers, date of

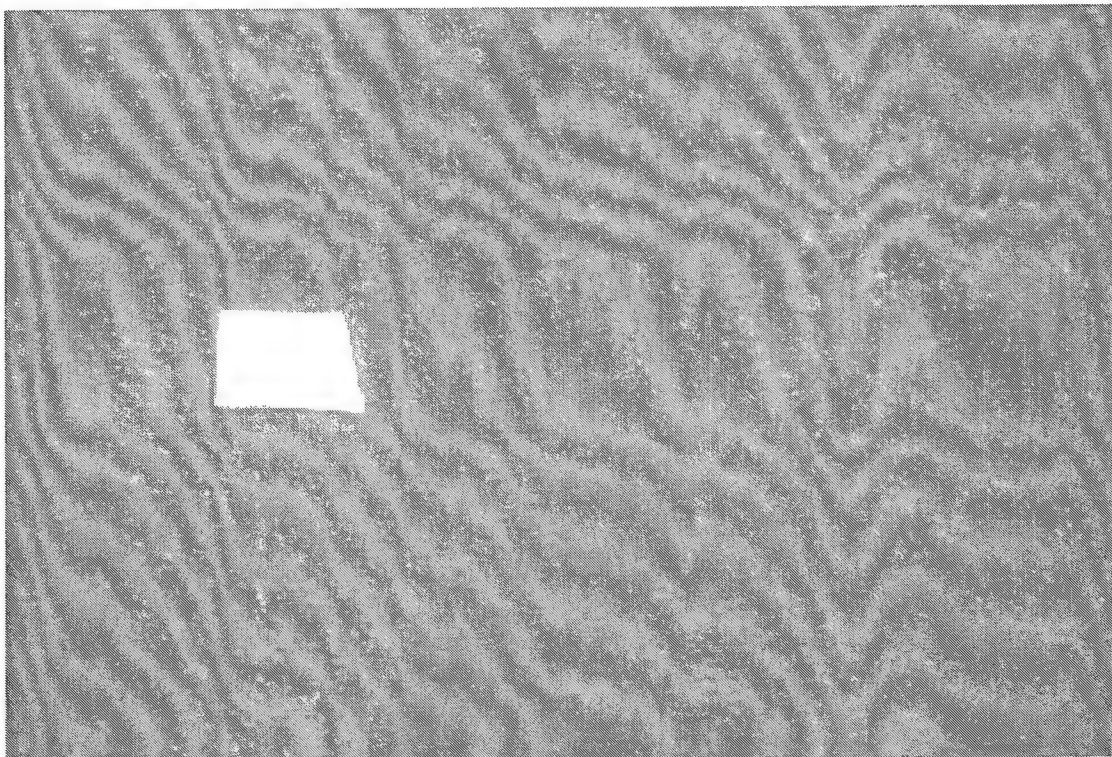


Figure 3.13 Surface texture of mixture 6, 4 months after placement.

construction, time after construction at which cracking was first observed, and the relative growth in crack width with time in the two coating areas. This table lists the maximum crack width at the time tested. Figure 3.14 illustrates crack severity through crack width versus time for two-coat mixtures 1 through 6 and 13 through 18, which were comparable, except for the use of a different coal tar emulsion. This figure shows that the rate of increase in the width of the cracks decreased with time, eventually reaching an equilibrium value after about 1 year.

The exact time of initial cracking was difficult to determine. The cracks were more visible on cloudy rather than bright sunny days. Either early morning or late afternoon sunlight was better than mid-day direct sunlight; however, indirect sunlight (cloudy weather) was best to observe the cracks. The size or width of the cracks was

Table 3.7 Time of Initial Cracking, Crack Width, and Cracking Patterns in Field Section												
Mix No.	Date Second Coating Completed (1997)	First Cracking, Days After Placement			Maximum Crack Width (mm) in						Crack Category	
		No. of Coatings			2 Coat Area, Days After Placement						Days ¹	
		1	2	3	268	323	379	443	589	739	379 ²	739 ²
1	11/4	281	248	248	---	---	---	0.55	0.60	0.60	2	2
2	11/3	---	249	268	0.40	0.55	0.55	0.55	0.60	0.75	3	3
3	11/4	442	248	309	0.40	0.65	0.80	0.80	0.90	1.20	3	2
4 ³	11/3	---	263	250	0.50	0.55	0.55	0.55	0.55	0.75	2	3
5	11/4	309	267	378	0.80	0.90	0.90	0.90	1.20	1.30	3	3
6	11/3	379	296	702	---	0.50	0.50	0.50	0.60	0.60	4	3
7	11/4	263	248	248	0.33	0.55	0.55	0.55	0.60	0.60	3	2
8	11/3	791	264	702	0.40	0.45	0.50	0.55	0.70	0.85	4	3
9	11/4	263	199	216	0.60	1.00	1.00	1.00	1.20	1.20	3	1
10	11/3	379	263	513	0.33	0.55	0.55	0.55	0.55	0.60	4	3
11	11/4	309	222	216	1.00	1.50	1.60	1.70	1.75	1.75	3	1
12	11/3	---	379	844	---	---	0.50	0.60	0.80	0.90	5	3
13	11/4	263	199	211	0.45	0.85	0.85	0.85	0.90	0.90	2	2
14	11/3	---	264	264	0.30	0.50	0.50	0.50	1.10	1.10	3	3
15	11/26	226	208	208	0.80	1.00	1.10	1.20	1.20	1.30	1	1
16	11/3	---	212	217	0.60	0.70	0.90	0.90	1.00	1.00	3	3
17	11/26	252	189	194	1.00	1.50	1.60	1.60	1.70	1.70	1	1
18	11/3	310	263	275	0.40	0.90	1.05	1.20	1.25	1.25	2	1
Notes:												
¹ Days from placement, based on placement on 11/3/97.												
² Ratings: 1- Large (≥ 1.10 mm (0.0433 in.)) interconnected cracks throughout; 2- Medium to small (< 1.10 mm (0.0433 in.)) interconnected cracks throughout; 3- Large or small isolated cracks, not throughout; 4- One or two short cracks (about 0.5 m (1 ft) or less in length); 5- No cracks.												
³ Sealer was placed without leaving an area with just one coating.												

monitored to assess the rate of cracking. The cracks were sized using a crack comparator, a clear plastic sheet with various line widths in millimeters marked on the sheet. This was used to determine the size of the crack opening at the surface of the sealer, Figure 3.15. Generally, the smallest crack that could be seen was about 0.1 mm (0.0039 in.) in width. The limitations to determining smaller crack widths

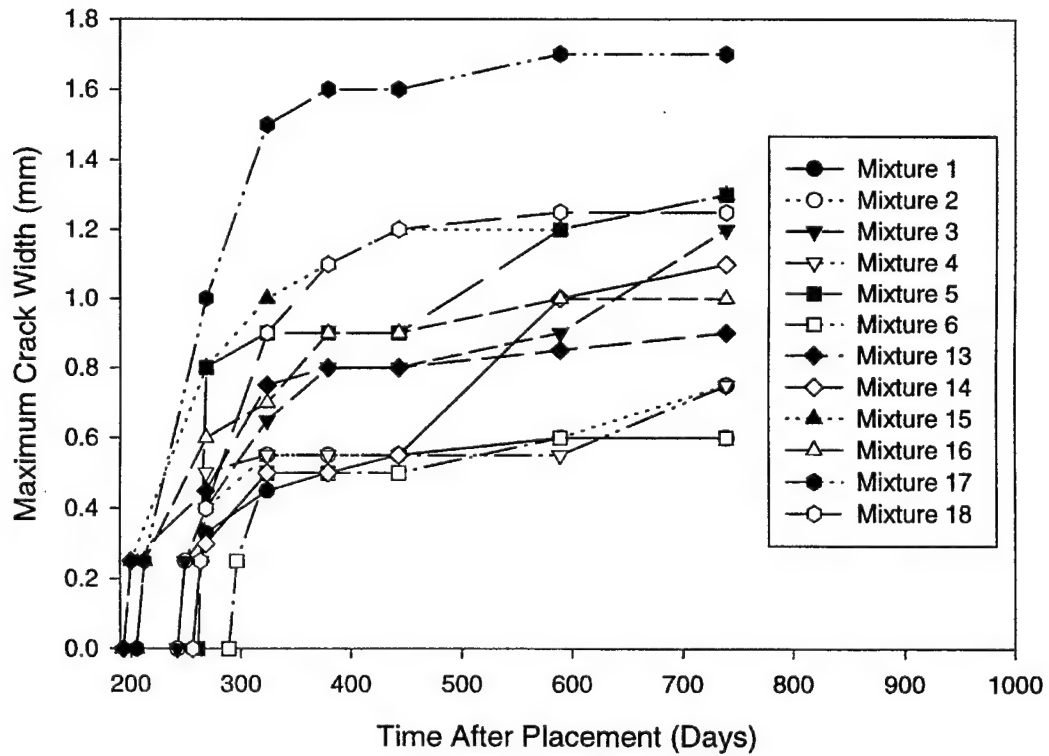


Figure 3.14 Increase in crack width, with time for two coat areas.

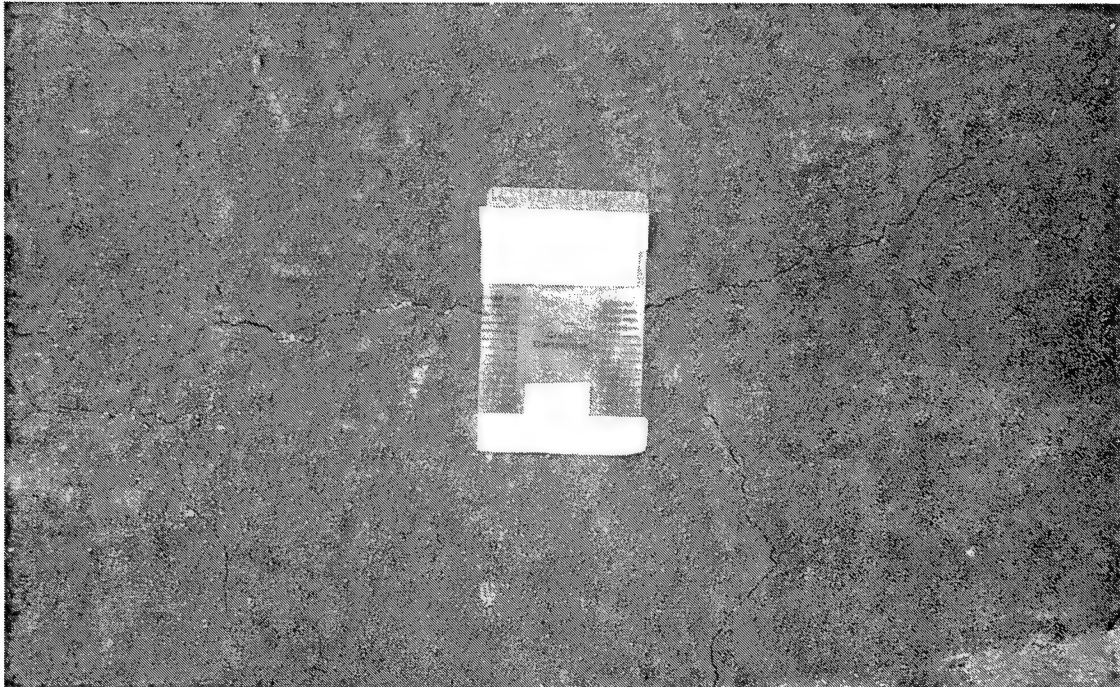


Figure 3.15 A crack comparator, used to measure crack width.

included the uneven macro-texture caused by the aggregate added to the mixtures. Because of the surface texture and the relative size of the sections, some type of field-portable visual enhancement method would have had to be developed to be able to find cracks smaller than about 0.1 mm (0.0039 in.). A suitable optical system was available in the laboratory, but it was not field-portable. Therefore, the presence and size of cracks were determined using only visual (unaided eye) means. It was recognized that cracks had most likely been present in a section for some time prior to where the cracks had progressed to the point where they were visible to the unaided eye. From the observed growth in crack width (Table 3.7), it could be estimated that the time between the crack occurring and it being visually detectable was probably relatively short.

Generally, in mixtures where early cracking occurred, mixtures 9, 13, 15, and 17, the cracking occurred in all three coating areas, Table 3.7. In mixtures 3, 5, 6, and 8, at least during the first summer, there was only minor cracking within the middle portion of the two-coat area. After one year, with only minor cracking, these mixtures could be considered to be in good to very good condition. All two-coat areas had some cracks within 300 days, except for mixture 12, which cracked about 375 days after placement. All three-coat areas cracked after about two years. After more than two years of field exposure, there were still no cracks in the one-coat areas of mixtures 2, 4, 12, 14, and 16. Considering the time until the first cracks appeared, cracking occurred in the largest (two-coat) areas first, while several of the smallest (one-coat) areas did not crack. The greater size of these larger (two-coat) areas possibly made crack detection easier than in the smaller (one- and three-coat) areas.

The thickness of the sealer applied could have had an effect on cracking and crack width, as the crack widths measured in the three-coat areas generally exceeded those obtained in the two-coat areas. It is important to note that none of the mixtures had cracks that followed between or along the line between the different coatings, Figure 3.16.

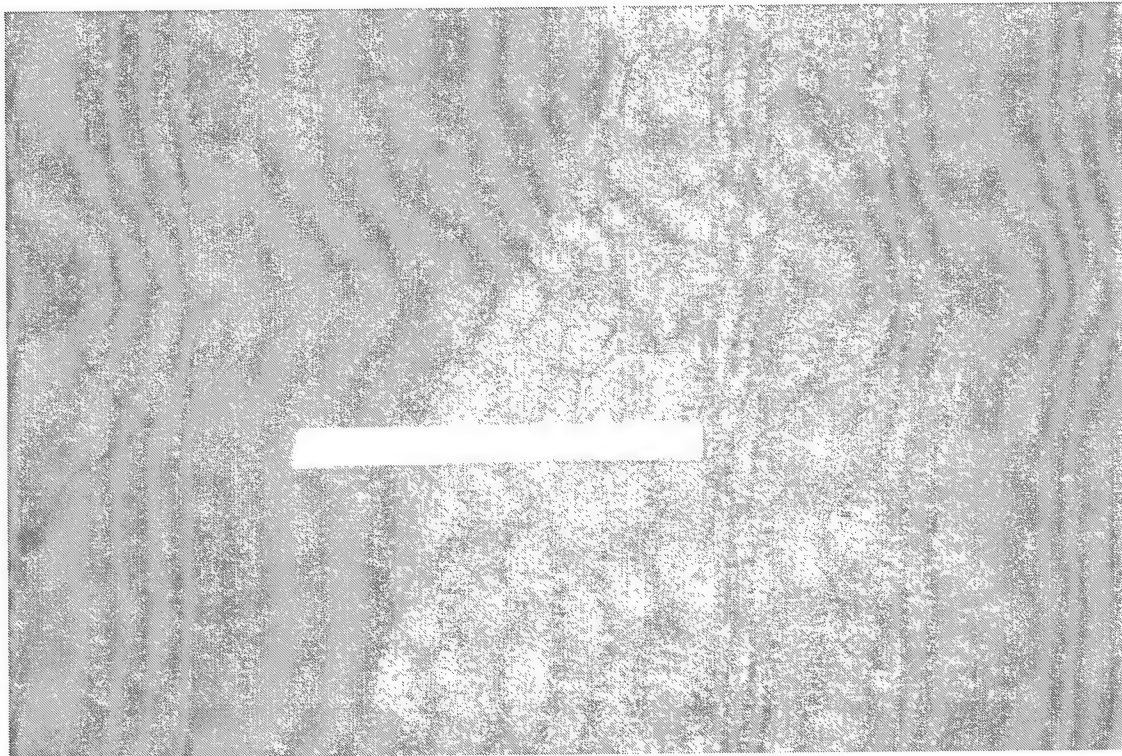


Figure 3.16 Intersection between one- and two-coating areas (one coat on left).

The cracked appearance of the two-coat areas, after the first year of field exposure, could be divided into five categories, Table 3.7. The breakdown was by large (1.10 mm or greater) and small (less than 1.10 mm) cracks and whether or not the cracks existed throughout the area and if they were connected together.

The cracking within the various mixtures two-coat areas, after about a two-year period, could be classified into three distinct categories. The first was where

relatively large interconnected cracks formed throughout the entire area, Figure 3.17.

The second was where smaller interconnected cracks formed throughout the entire area, Figure 3.18. The third was where the cracks, whether large or small (usually a mixture of both) were relatively isolated and not connected together, Figure 3.19.

There were often areas up to a square meter (yard) or more without cracks. The extent of cracking within the two-coating area is illustrated in Figure 3.20 by plotting the cumulative percentage of area with cracks versus time after placement. This figure shows the amount of cracking increased with time and that more than one-half of the mixtures had cracked throughout their area in less than 700 days.



Figure 3.17 Large cracks throughout two-coating area of mixture 15.

A comparison of Figures 3.14 and 3.20 shows that mixtures with increased amounts of aggregate (open markers in Figures 3.14 and 3.20) generally had fewer cracks and smaller crack widths. These figures also show that the mixtures containing

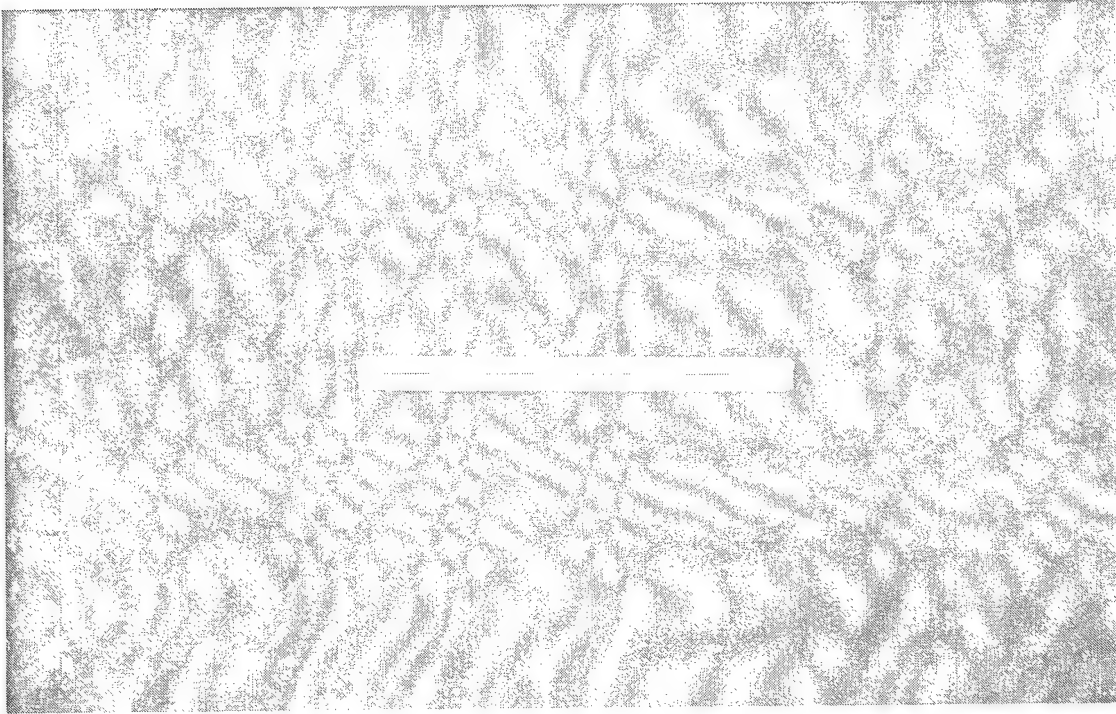


Figure 3.18 Small interconnected cracks in mixture 13.

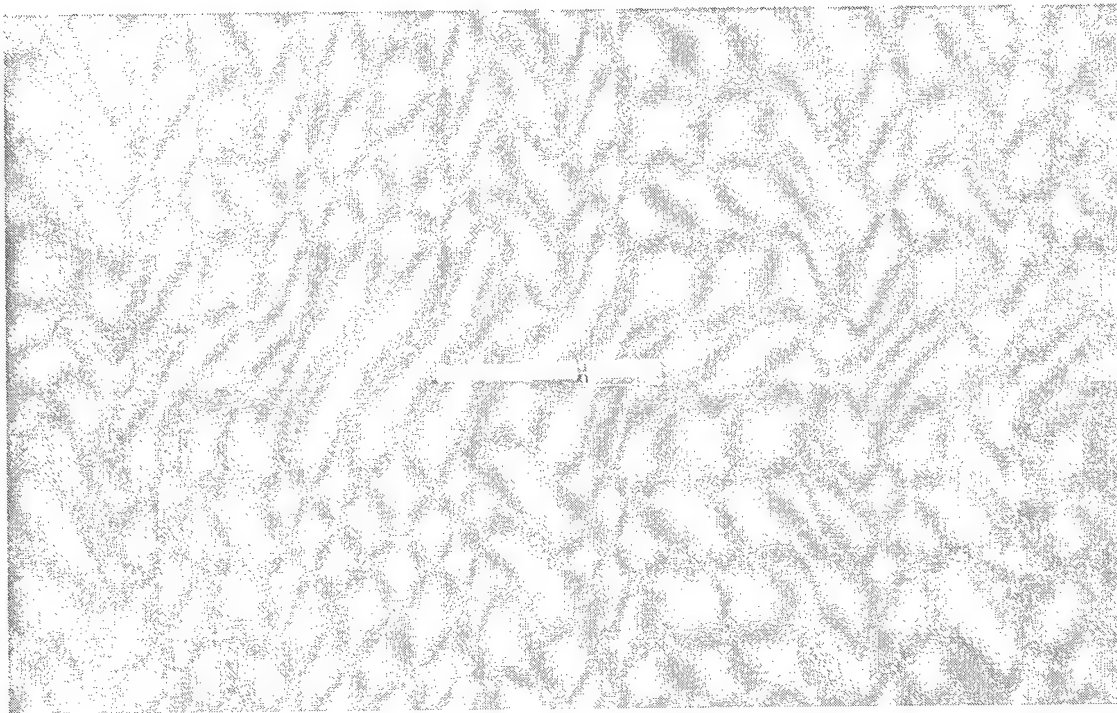


Figure 3.19 Mixture 2, containing variable crack width and density.

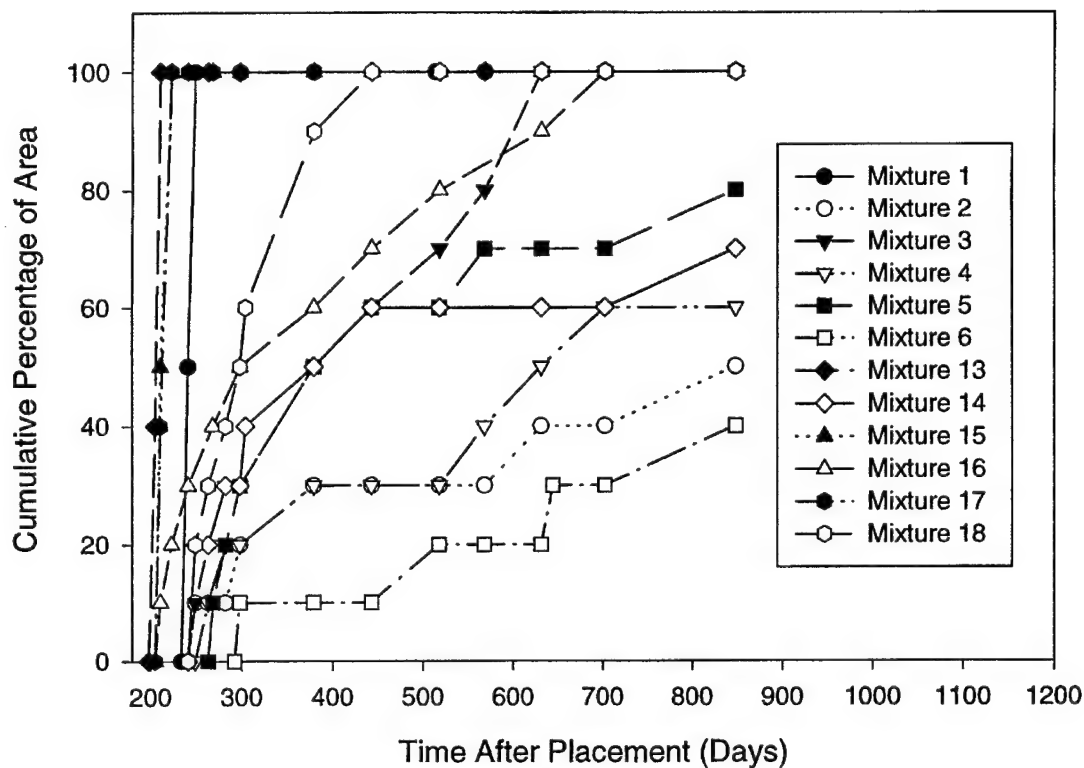


Figure 3.20 Cumulative amount of cracking in two-coating areas versus time from placement.

emulsion from manufacturer No. 1 generally had smaller areas of cracks and smaller crack widths when compared to those containing the emulsion of manufacturer No. 2.

Climatic Information

A weather station was placed next to the field evaluation section to gather information on air temperature and pavement surface temperature on the existing and sealed pavement. The weather station began collecting data from the field site on 6 February 1998. The station was battery powered and had a solar trickle charger. The station recorded the air temperature and also had two inputs for two pavement temperature values. The pavement temperatures were obtained using thermistors epoxied to the pavement. Prior to placement, the thermistors were calibrated and

temperature variations between the thermisters and the calibrated control temperatures were less than 0.3°C (0.5°F). One thermister was placed directly on one of the test mixtures (Mixture No. 10) and the other was placed on the unsealed surface of the existing asphalt pavement next to the sealed pavement, see Figure 3.21. The data for these temperatures was taken on separate channels, for each of the three parameters collected. Obtaining a reading from each sensor every hour, the onboard storage capacity of the weather station was several months, although readings were generally down loaded every few weeks. Figure 3.22 provides the average air and pavement temperatures that occurred during the time frame of the evaluation of the field section.

The temperature difference between the two thermisters, during extended periods of sunlight, ranged from 2 to 4.5°C (4 to 8°F), see Figure 3.23. This was



Figure 3.21 Thermisters, epoxied to the sealer and the surrounding pavement surface.

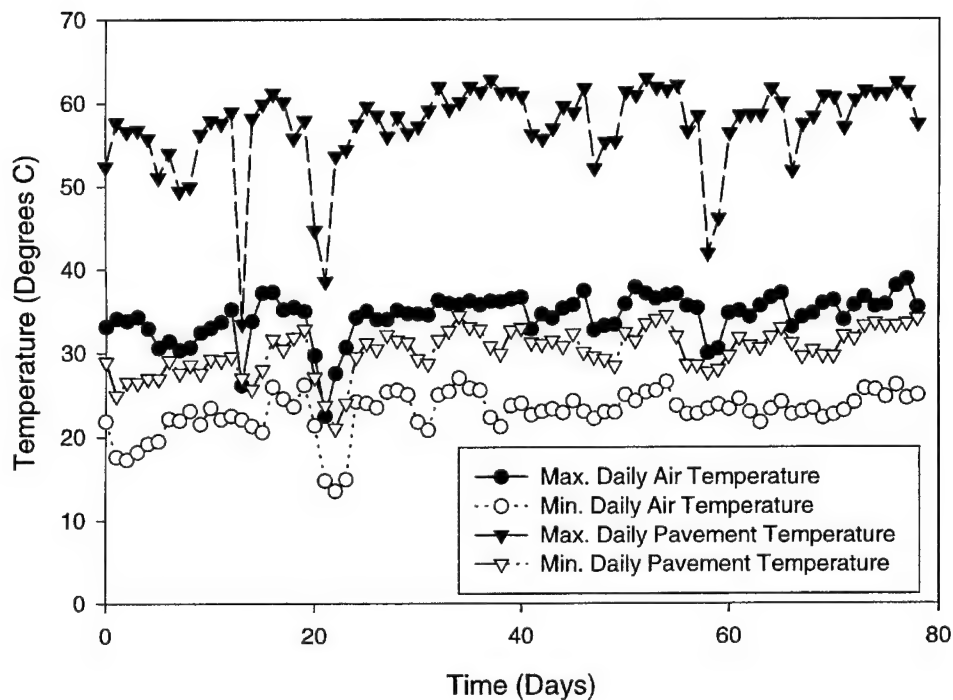


Figure 3.22 Typical maximum air and sealed pavement temperatures from mid May 1998 to the end of July 1998.

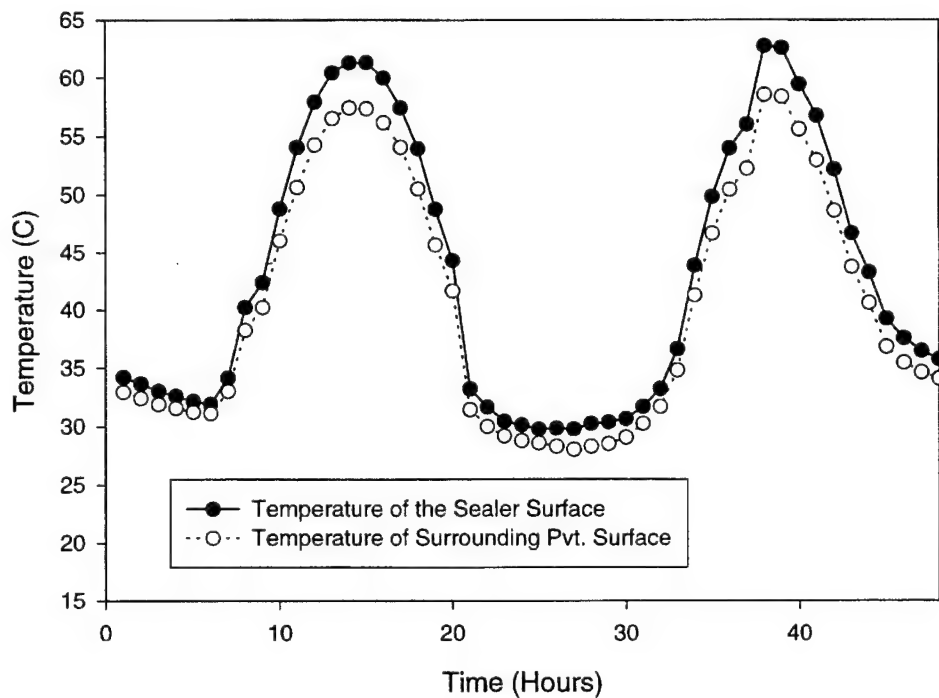


Figure 3.23 Typical pavement temperature variations during a sunny day.

expected because of the blacker surface of the sealer mixture than that of the surrounding pavement.

Cores Through Cracks

Seven 100 mm (4 in.) core samples were taken through various cracks that had occurred in the coal-tar mixture field section two years after placement. These cores were used to investigate whether the cracks in the sealer extended into the underlying hot-mix asphalt pavement. The cores were taken through a variety of cracks, from the largest to the smallest, see Figure 3.24. Table 3.8 gives the location and crack width through which the cores were taken. Core number seven was taken on the edge of mixture 4, where a crack could be seen running from the sealed area into the unsealed pavement. This was the only observable occurrence of a reflection crack within the entire test section. There was no visible evidence of the sealer not being bonded to the underlying hot-mix pavement.

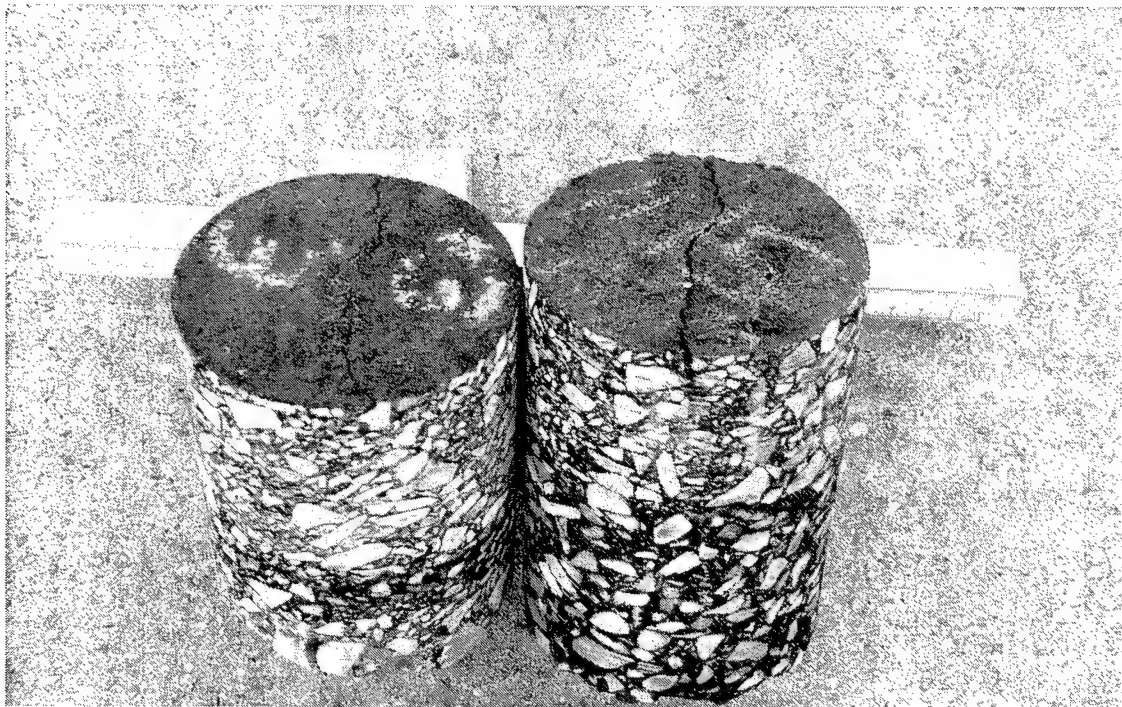


Figure 3.24. Field cores taken through cracks in mixtures 3 and 15.

Table 3.8 Field Core Information				
Core Number	Mixture Number	Crack Width (mm)	Number of Sealer Coatings	Cracking in Underlying HMA ¹
1	1	0.50	2	No
2	3	0.85	2	No
3	4	0.60	2	No
4	4	0.80	1	Yes ²
5	5	1.20	2	No
6	15 ³	1.05	2	No
7	15 ³	2.60	3	No
¹ The cores were visually inspected for cracks ² This core was taken over a crack that extended through the hot-mix asphalt into an unsealed area of the pavement. ³ These largest cracks had upturned edges.				

Pull-Off Strength

The pull-off strength of the various coal-tar sealer mixtures was evaluated with an Elcometer device. This device is defined in ASTM D 4541 as a fixed-alignment adhesion tester. The test involves epoxying a 40 mm (1.57 in.) diameter *dolly* (aluminum test plug) to the coal-tar sealer in an area with no visual cracks. The pull-off strength is obtained by determining the greatest perpendicular force (in tension) that can be exerted on surface of a plug. Failure types could be classified as either cohesive (within the mixture itself) or adhesive (pulling the mixtures intact from the surface). Table 3.9 lists the type of failure and the force required too pull the dolly from the surface for the various mixtures tested. The strength values obtained represent the maximum tensile strength of the mixtures at the given temperature at the time of the test. These tests were conducted after the mixtures had been in place for slightly more than two years. Tests indicated that the mixtures with lower amounts of aggregate tended to fail in adhesion (pulled away from the HMA), while those with

Table 3.9 Tensile/Cohesive Strength of Field Test Section Mixtures			
Mixture ¹	Test Temperature, °C (°F)	Type of Failure ^{2,3}	Pull-Off Strength ³ , kPa (psi)
1	49 (120)	Cohesive/Adhesive	776(112)/ 648 (94)
2	49 (120)	Cohesive	560 (81)
3	49 (120)	Adhesive/ Adhesive	733 (106)/ 733 (106)
4	49 (120)/ 43 (115)	Cohesive/ Cohesive	362 (53)/ 345(50)
5	49 (120)/ 45 (115)	Adhesive/ Adhesive	517 (75)/ 776 (112)
6	49 (120)	Cohesive	776 (112)
13	44 (115)	Cohesive	648 (94)
15	45 (115)	Cohesive (25% Adhesive)	733 (106)
¹ Mixtures correspond to those listed in Table 3.5.			
² Cohesive is failure within the mixture itself, adhesive failure is pulling off or apart from the surface of the HMA.			
³ Results based on one or two tests as given.			

higher amounts of aggregate failed in cohesion. The adhesion failures indicate that the tensile strength of the sealer exceeded the tensile or cohesive strength of the underlying HMA. The mixtures with lower amounts of aggregate generally have higher tensile strengths.

SUMMARY

Various coal-tar sealer mixtures were safely placed in a field test section and monitored for about 2 years. The mixtures used coal-tar emulsions from two manufacturers with varying amounts of aggregate and polymer. Comparative laboratory samples were made and exposed to the same field conditions. Because coal-tar emulsions are colloidal systems, the samples were poured into molds on a flat surface and allowed to cure. Air and pavement temperatures were recorded for the duration of the study. The mixtures were visually monitored for cracking. Tests were conducted for depth of cracking and field tensile strength.

All the coal-tar sealer sections developed at least one crack within about one year of placement. The evaluation of field results, Table 3.7, shows that coal-tar mixtures with higher amounts of aggregate showed less cracking than mixtures with lower amounts of aggregate.

A difference in temperature due to color was evidenced by a difference in temperature between sealed and unsealed field test pavement surfaces, Figure 3.23. On sunny days this temperature difference would reach about 4.5°C (8°F).

The cracks in the coal-tar sealers originated in the sealer and were not evident in the underlying HMA. Pullout tests on the sealer mixtures did not show great differences in tensile strength values. However, the adhesive failures of most mixtures with lower amounts of aggregate indicate that they have a somewhat higher tensile strength.

CHAPTER 4: LABORATORY METHODOLOGY

INTRODUCTION

A series of laboratory experiments were conducted on some of the coal-tar sealer materials and mixtures as used in the field evaluation. The laboratory study concentrated on mixtures 1 through 6 and 13 through 18, which were duplicate mixtures except for the use of coal-tar emulsions from two different manufacturers, Table 3.5. Conventional evaluation methods, as used in the sealer industry, were performed as specified in ASTM and research publications (ASTMb 1999, Shook et al. 1990, and Sebaaly et al. 1999). The non-conventional methods for this study included the development of new evaluation methods and procedures and the adaptation of several Strategic Highway Research Program (SHRP) binder evaluation methods.

Several of the non-conventional evaluation methods investigate the rheological properties of the coal-tar mixtures. Coal-tar sealers and the underlying hot-mix asphalt (HMA) exhibit viscoelastic behavior and the Maxwell, Kelvin, and Burgers models discussed in Chapter 2 can be used to represent a mathematical description of this behavior. These models also present some of the complexities involved with engineering materials. Temperature was not mentioned in regards to the models, although it is critical to the viscoelastic behavior of the sealer/HMA pavement structure. At low temperatures, elastic properties are usually predominate, while at higher temperatures binder materials generally behave more like a liquid and viscosity is most important. At normal pavement temperatures the binder in the sealer and the HMA behave as viscoelastic materials.

CONVENTIONAL EVALUATION METHODS

Several conventional performance/evaluation methods have received some acceptance in coal tar sealer specifications. These include tests for fuel resistance, viscosity, and freeze-thaw tolerance.

Fuel Resistance

The test for fuel resistance is widely used and accepted within the coal tar sealer industry. It has been used for mixture evaluation for more than 15 years and is currently defined in ASTM D 2939 (ASTM 1999). This procedure utilizes kerosene as the fuel or solvent material. An overview of the test procedure is as follows: (1) A white ceramic tile is covered with two coats of a coal tar sealer of a given mixture, each coat is allowed four days to cure; (2) A metal ring approximately 50 mm (2 in.) in diameter and 25 mm (1 in.) high is attached to the cured sealer with a fuel resistant silicone sealant material, see Figure 4.1; (3) Kerosene is then placed inside the metal ring and after 24 hours the sample is evaluated; (4) If the tile has discolored that indicates that the coating is not fuel resistant; however, even if the kerosene has discolored and the coal tar surface is slightly softened, if the tile has not discolored the sealer passes the fuel resistance test. The kerosene will always discolor when exposed to the coal tar surface during the test, whether it passes or not; therefore, if the kerosene is able to flow through the sealer to the tile, it will stain the tile, see Figure 4.2.

Viscosity

Viscosity can be simply defined as the resistance to flow of a fluid. When the ratio or the results are independent of the rate of shear, the material is said to be Newtonian. The viscosity of most pavement binder materials including coal tar

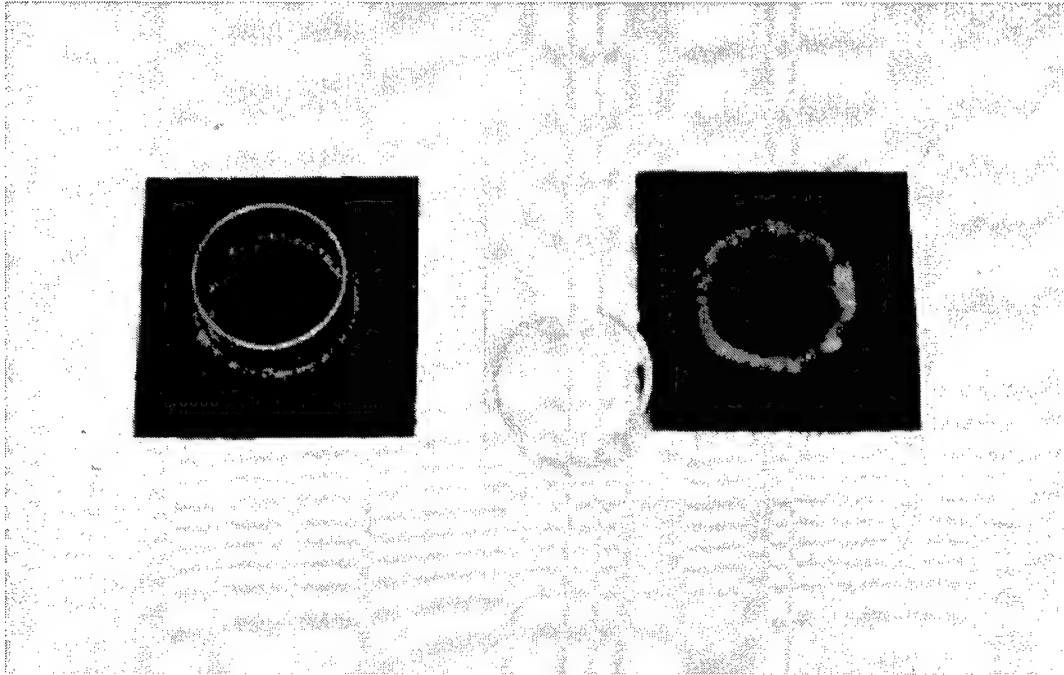


Figure 4.1 Preparing specimens for kerosene test.

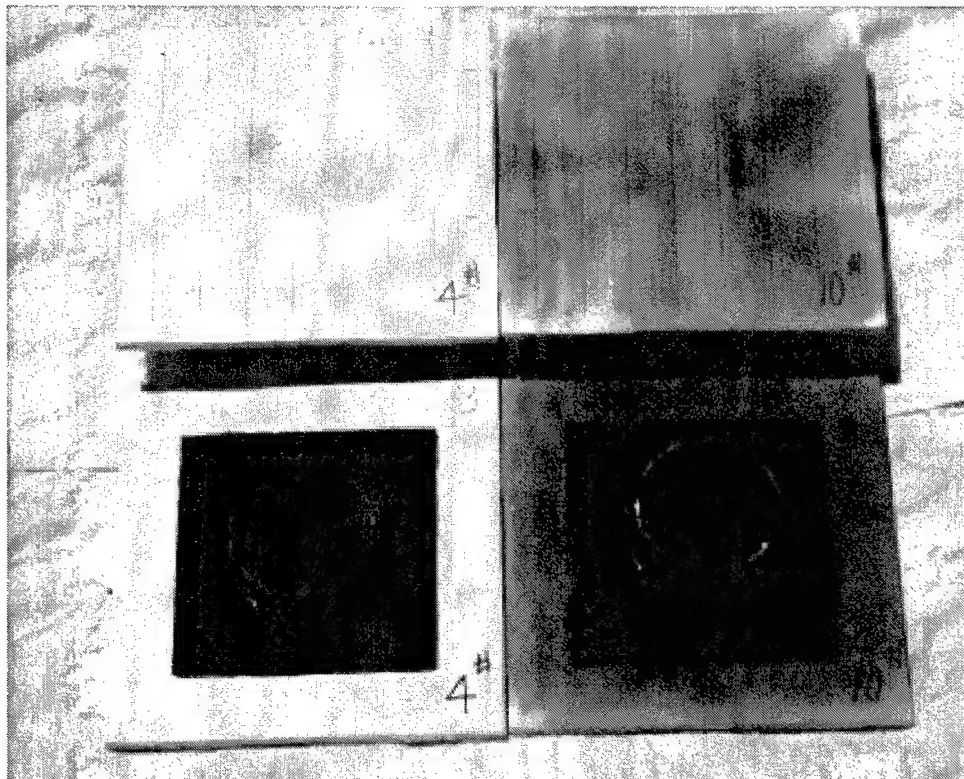


Figure 4.2. Slight failure of specimens on left, complete failure on right.

change with the rate of shear and they are therefore considered non-Newtonian (Hunter 1994). In non-Newtonian materials, such as coal tar, during flow the non-symmetrical objects (coal-tar and clay colloidal particles) pass by each other and their size, shape, and cohesiveness determine how much force is required to move them. A change in the rate of shear will change the particle alignment and result in a change in the force required for movement. Coal-tar emulsions can be described as having properties of both shear thinning and thixotropic materials (Shook et al. 1989). Shear thinning can be described as a reduction of viscosity with an increasing rate of shear, Figure 4.3. These properties are similar in that they describe a material that decreases in viscosity under shearing, and decreases more with increased rates of shear, and will increase in viscosity with the removal or decrease of the shear loading. Thixotropy can be described as a decrease of the apparent viscosity under constant shear stress or shear rate, followed by a gradual recovery when the stress or shear is removed or the shear rate is decreased. The effect is time dependent, Figure 4.4. Thixotropic materials when subjected to application of shear stress have a breakdown in structure followed by a reduction in viscosity. When this stress is released the original structure is re-established over time (RRL 1962). Viscosity can be measured by several methods, depending on the flow properties of the material. An absolute measure of viscosity is the ratio between the applied shear stress and the rate of shear. The normal unit of measurement of this viscosity is the poise (1 g/cm^2).

The viscosity of the seal coat is most important in regard to application. The coal tar mixture must be wet enough to allow for even application and to adhere to the surface of the pavement. If the mixture is too wet (low viscosity), it will not be able to

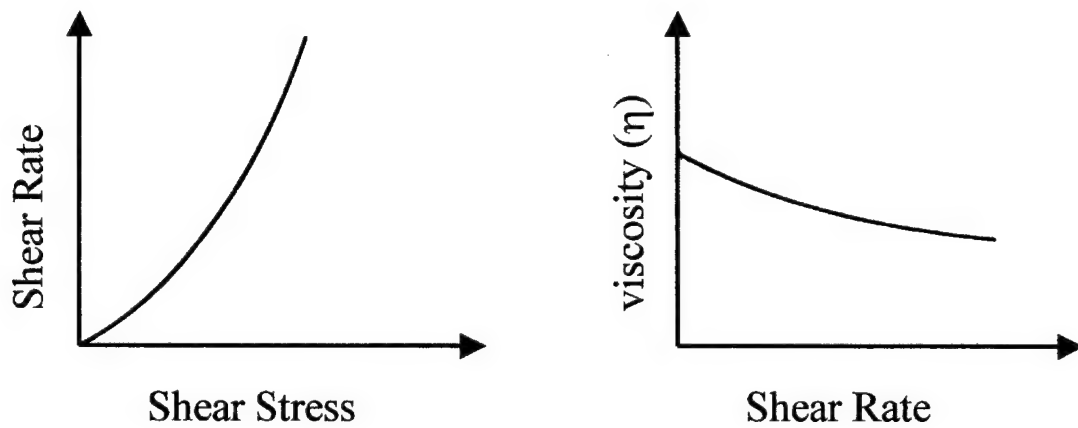


Figure 4.3. Typical behavior of a shear-thinning or pseudoplastic fluid.

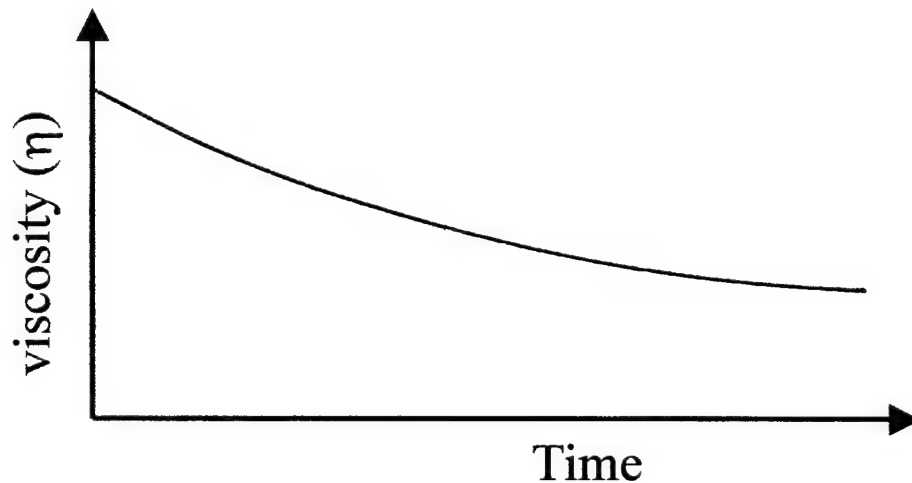


Figure 4.4 Viscosity versus time of a thixotropic fluid under a constant rate of shear.

hold the aggregate in suspension. If the mixture is too dry (too high a viscosity), it will not spread evenly and adhere to the surface. There must be enough moisture present to allow for proper spreading and to counteract the surface tension of the pavement and allow the sealer to adhere to the surface. Where a spray application is

to be used, the mixture must be viscous enough to allow for spray application.

Mixtures with relatively high viscosities may not be suitable for spray application because of pumping and spraying requirements. However, they may be acceptable for application with hand squeegees, depending on climatic and pavement surface conditions.

Several researchers and material manufacturers have investigated the viscosity of coal-tar emulsion mixtures (Shook et al. 1989 and Schlake 1997). The viscosity of coal-tar emulsion mixtures has been found to vary with the volume of the components within the mixture. Shook et al. established a range of viscosities for coal tar sealer mixtures using a Brookfield viscometer at a shear rate of 50 RPM. A range of viscosities from 10 to 90 poises was established for the mixtures, both with and without aggregate. Because of the shear thinning properties of coal-tar emulsion mixtures, the Thomas-Stormer Viscometer also has been widely used to measure viscosity (Schlake 1997). This paddle bladed viscometer is widely used by the paint industry.

The viscosity of mixtures 1 through 6 and 13 through 18 (see Table 3.5) were determined with a Brookfield Model DV-II + viscometer, using spindle No. 27, Figure 4.5. The testing was confined to these mixtures because they represent six different types of formulations, with the differences between 1 through 6 and 13 through 18 being a different coal-tar emulsion and polymer additive manufacturer.

Freeze-Thaw

The freeze-thaw properties of sealer mixtures are important in cold climates. This importance is increased in areas where the sealers are exposed to a substantial number of freeze-thaw cycles. A test method that evaluates cracking potential would

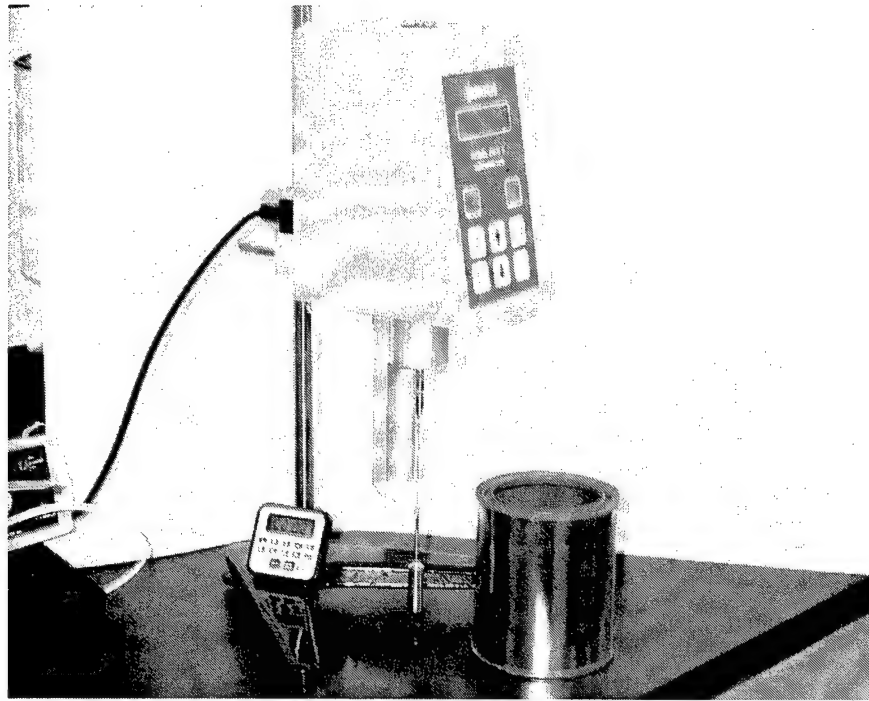


Figure 4.5 Brookfield Model DV-II Viscometer.

appear viable because cracking is the most common failure method of sealers encountered in the field. However, the cracking that occurs in the field is not necessarily related to freezing, as similar cracking occurs in sealers where freezing temperatures are never reached. Nevertheless, the method may provide an indication of comparative field performance between various mixtures.

A FAA study found that a wet freeze-thaw test was the most severe type of test and showed promise for measuring the relative performance between mixtures (Saraf, Majidzadeh, and Kumar 1992). The test procedure developed involved observing the development of cracking between freeze-thaw cycles of a coal-tar mixture on an asphalt shingle. Recent work on a freeze-thaw test method has also shown that an asphalt shingle will provide a satisfactory surface on which to place the mixture (Sebaaly et al. 1999). The procedure developed by Sebaaly was used to evaluate

several of the mixtures used in the field test sections. There were several difficulties and unknowns in the method as provided. No allowance is given for a time interruption between test cycles, the requirement of 24-hour heat and cold cycles and one-hour soak periods in between would not allow for testing within a normal work day. The type of shingle required for the test is not well defined. Standard or common residential asphalt roofing shingles have a bead of asphalt down the middle on both the rough and the smooth side of the shingle. This bead will melt and flow during heating and would have to be considered during the evaluation of the sealer mixtures performance. The shingle required for the test is a rolled shingle, from which a 300-mm (12-in.) square can be obtained as the test medium. These test procedures all require extended time to complete ten cycles of freezing and thawing. Even conducting tests continuously, over weekends and holidays, requires about three weeks for completion.

Several mixtures were evaluated using the procedures as outlined by Sebaaly. However, a more workable alternative method was also evaluated. In this procedure a cycle is completed within 24 hours, making it easier to schedule and testing can be interrupted over weekends and holidays. Specimen fabrication is the same as developed by Sebaaly, except that the mask has a 25 × 25 mm (10 × 10 in.) inside opening. The procedure involves a 24-hour cure after specimen preparation. The specimen is submerged in water for one hour and excess water is allowed to drain off. The specimen is placed in a freezer at -10°C (26°F) for five hours and then in a forced draft oven for 16 hours. Allowing the specimens to cool for one hour after heating and to warm for one hour after freezing, results in a 24-hour test cycle. The times given

did not vary by more than 5 minutes during the testing. The soaking and freezing cycles are repeated for up to 10 cycles. A grid frame made of wood and fishing wire was used to divide the specimen into 100 equal squares, (Figure 4.6). The squares containing cracks of each specimen are counted to determine the percentage of cracked area. The final test procedure used is outlined in Appendix A.

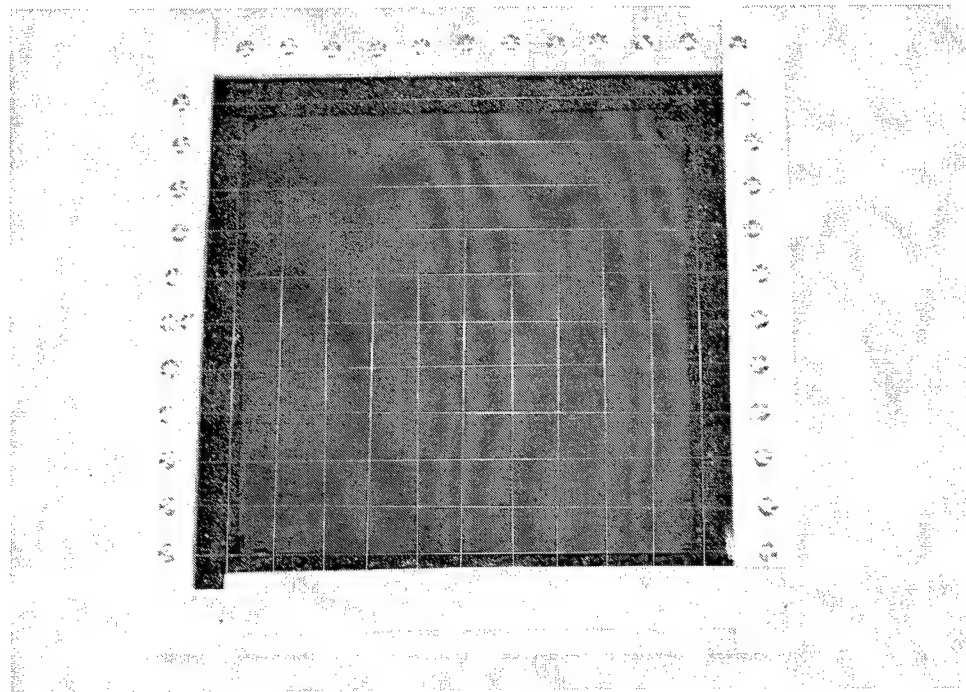


Figure 4.6 Grid frame over freeze-thaw test specimen.

NON-CONVENTIONAL EVALUATION METHODS

Bending Beam Rheometer

The bending beam rheometer (BBR) was used to evaluate various binder material formulations. The test apparatus and procedure (AASHTO TP1 1996) are devised to provide the creep stiffness at a selected temperature and loading rate or time. The standard procedures were used with some adjustments for the varying beam sizes of the sealer specimens. The test apparatus is designed to do a center point

loading of a beam in pure bending with static loading and no torsional loads. Before and during the test the temperature of the samples is held constant. A beam of known dimensions is loaded between supports placed 100 mm apart with a 100 g load for four minutes, Figure 4.7. The deflection of the beam at any given time can be calculated using the simple beam equation for a concentrated center point loading. The deflection is dependent on the span length, loading, and beam geometry as shown below:

$$\delta_t = \frac{PL^3}{48 S_t I} \quad (4.1)$$

where

δ_t = deflection at time t

L = the span length, mm

S_t = stiffness at time t, kpa

I = moment of inertia

P = concentrated center load, g

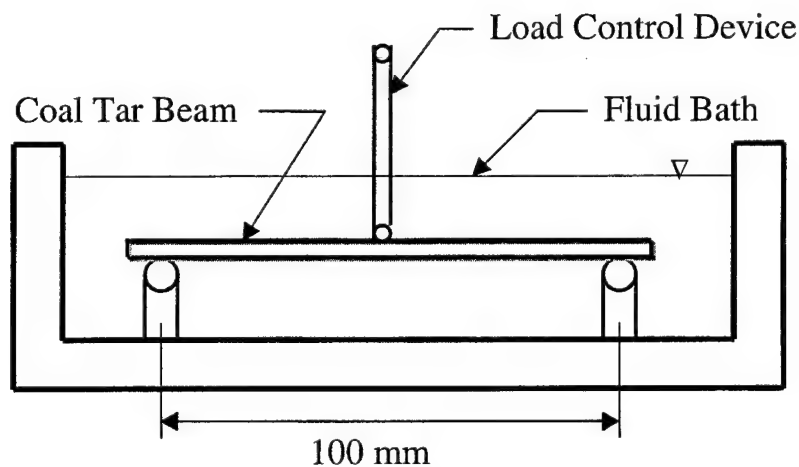


Figure 4.7 Schematic Layout of Bending Beam Rheometer.

The moment of inertia (I) of a rectangular beam = $1/12 bh^3$

where

b = beam width, mm

h = beam height, mm

Therefore the stiffness (S) at time (t) can be found using the measured deflection as shown below:

$$S_t = \frac{PL^3}{4bh^3\delta_t} \quad (4.2)$$

Incorporating the constant value used for L, the formula for flexural stiffness becomes:

$$S_t = \frac{250,000 P}{bh^3\delta_t}$$

The deflection obtained will increase with the duration of the test; therefore the stiffness will decrease as a function of time (Kennedy et al. 1994).

Values for the creep stiffness and the slope of the stiffness curve for asphalt binders are determined after loading for 60 seconds, which considering minimum pavement temperature and time-temperature relationships corresponds to a pavement loading time of 2 hours. This relationship may not be the same for coal tar sealer mixtures, because of the different binder and aggregate gradation used. Nevertheless, 60 seconds was used as the time for a comparison between various coal tar formulations and changes with time.

Dynamic Shear Rheometer

The dynamic shear rheometer (DSR) test apparatus and procedure (AASHTO TP5) provide time-temperature properties of asphalt cements. The DSR, applies an oscillating shearing load to a specimen at a selected frequency and temperature. A

range of frequencies and temperatures can be used to develop the time-temperature properties of the material tested. The method uses a 1 to 2 mm (0.039 to 0.079 in.) thick sample of binder material between two (8 or 25 mm (0.315 or 0.984)) parallel circular plates. The specimen thickness and the plate diameter required are dependent on the stiffness of the binder (Kennedy et al. 1994). The bottom plate is fixed and the top plate is oscillated by a computer-controlled electronic motor. The oscillations are typically less than 0.1 degrees for asphalt binders. The actual amount of oscillation will depend upon the binder and the test temperature. The frequency is normally selected to relate to the rate of loading the binder will experience under field conditions. This can vary from one radian per second for very low speed or standing traffic to ten radians per second for traffic moving at a speed of 100 km/hour (62 miles/hour).

The test procedure requires the measurement of the angular rotation, θ , and the applied torque, τ . The shear stiffness (complex modulus), G^* , is calculated using Equation 4.3.

$$G^* = \tau_m / \gamma_m \quad (4.3)$$

where

G^* = the complex shear stiffness modulus, kPa

τ_m = maximum shear stress (peak to peak), kPa

γ_m = maximum shear strain (peak to peak)

The peak-to-peak values are obtained by taking the difference between the maximum and minimum shear stress and shear strain, respectively. The shear stress, τ , can be calculated from Equation 4.4.

$$\tau = 2T/\pi r^3 \quad (4.4)$$

where

T = applied torque

r = radius of the plate

The shear strain, γ , is calculated using equation 4.5.

$$\gamma = \theta r/h \quad (4.5)$$

where θ = deflection or angle of rotation.

Viscoelastic materials exhibit a delayed response between an applied shear stress and the resultant shear strain, Figure 4.8. Figure 4.9 shows this delayed response relationship in terms of G^* . The phase angle can also be determined from the time lag between the applied shear stress (torque) and the resulting shear strain (angular rotation), as used in a stress-controlled test. The phase angle, δ , can be obtained by multiplying the time lag, Δt , by the angular frequency, ω , as shown in Equation 4.6 or directly from test results in terms of degrees per loading cycle, as given in Equation 4.7.

$$\delta = \omega (\Delta t), \text{ degrees} \quad (4.6)$$

where

ω = angular frequency

Δt = time shift (time lag)

$$\delta = 360 (\Delta t/t), \text{ degrees} \quad (4.7)$$

where

t = time for one cycle

It can be calculated in terms of radians as shown in Equations 4.8 below:

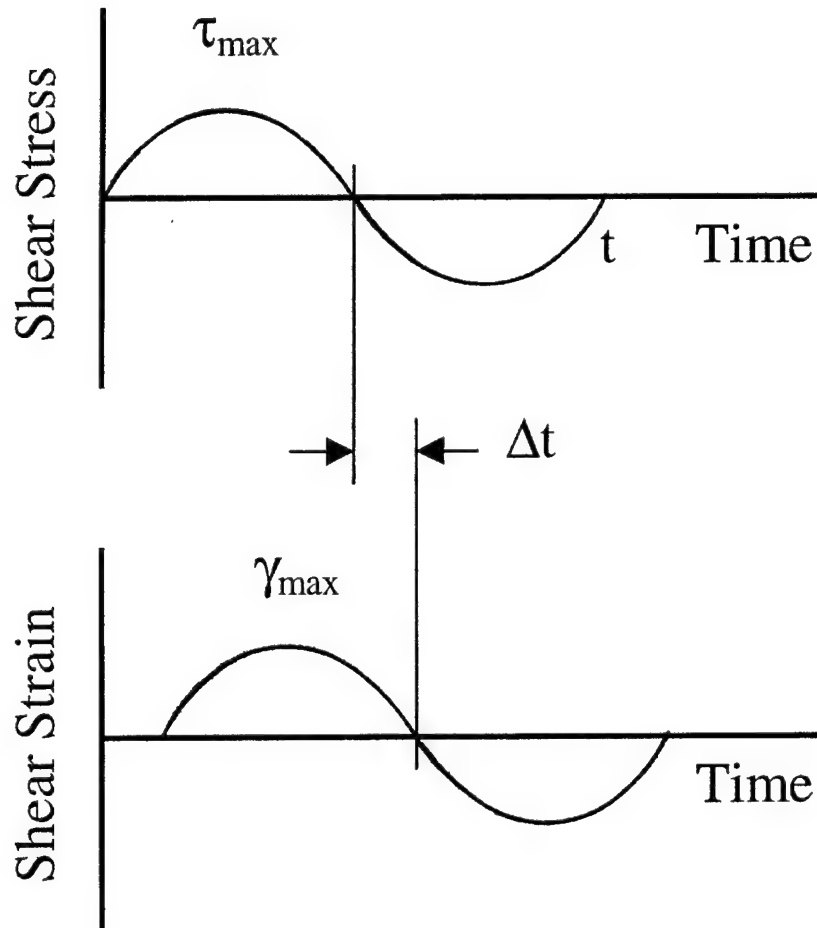


Figure 4.8 Relationship of applied shear stress to resulting shear strain for viscoelastic materials.

$$\delta = 2\pi (\Delta t/t), \text{ radians} \quad (4.8)$$

The phase angle or phase lag, for viscoelastic materials will vary between 0 and 90 degrees. For totally elastic materials there is no lag between applied shear stresses and shear strain response and δ will equal zero degrees. A totally viscous material would have δ equal to 90 degrees. At high temperatures, δ approaches 90 degrees while at low temperatures δ approaches zero degrees. As shown in Figure 4.9, the value of δ is related to the value of the loss, G'' , and storage, G' ,

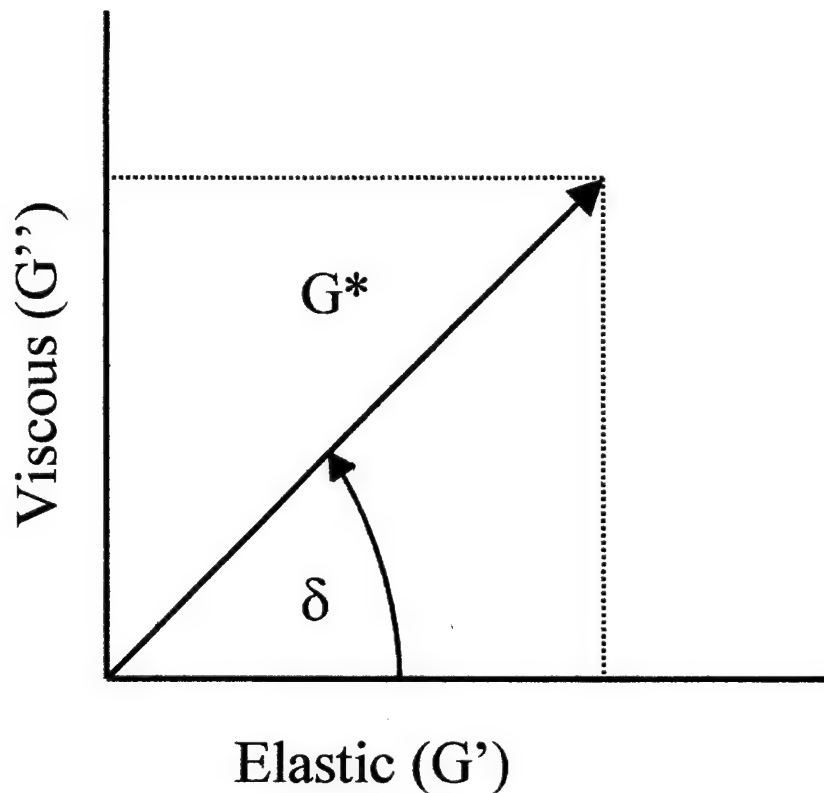


Figure 4.9 Graphical representation of the components of the complex shear modulus G^* .

moduli. The values of G'' and G' can be considered to be the respective estimates of the viscous and elastic components of the complex shear modulus (G^*).

The DSR was used to evaluate the properties of the various base coal tars. Despite numerous attempts, the DSR could not be used to evaluate the corresponding coal-tar emulsion and coal-tar sealer mixtures, even at temperatures up to 140°C (284°F). Standard test procedures, using two 25-mm parallel circular plates, were used with the base coal-tar materials from both manufacturers. These tars were evaluated at temperatures ranging from 20 to 30°C (68 to 86°F). Tests were conducted every 5°C, instead of the 10°C interval normally specified for asphalt cement binders, because of the temperature susceptibility of these tars. This

temperature susceptibility caused the tar to be too stiff at temperatures lower than those given above. At higher temperatures, above 30°C (86°F), the tar became too soft or fluid to obtain satisfactory results.

Uniaxial Tension

The stress related evaluations included uniaxial direct tension tests on each mixture type to determine the maximum tensile strength at the given strain rate and temperature. The results of these tests were used to select a loading value for stress-relaxation tests on the various coal tar sealer mixtures. The procedure for conducting stress-strain and stress-relaxation evaluations of the various coal tar mixtures was developed using specimens manufactured in the laboratory. These tests were performed on a computer controlled, hydraulically driven, loading apparatus.

In order to obtain accurate measurements of stress and strain a “dog-bone” shaped specimen was required. This shape avoids the problem of stress concentrations at the point of the gripping mechanism that provides the desired tension on the specimen. The measurements of displacement under a given load and loading rate will take place in the narrow center section of the specimen. In this section a uniform tensile stress is applied across the specimen during the test. The stress (σ) developed can be computed from Equation 4.9 below:

$$\sigma = \frac{P}{A} \quad (4.9)$$

where

σ = stress

P = applied load

A = cross-sectional area of specimen

This formula is appropriate provided that the cross-sectional area does not decrease during the loading and is valid for small strains, generally less than 1 percent of the gage length. The use of this formula also requires the assumptions of a homogeneous material, static (not dynamic) axial (in all planes) loading, and no residual stresses within the specimens. The process involved in fabricating the dog-bone shaped specimen probably created regions of stress concentration where angled cuts were made to create the end of the specimen (increase in the specimen width). Any specimen that failed in the area of these cuts was eliminated from consideration.

The specimens were attached to the testing machine by metal gripping jaws. The bottom jaw was fixed in all axes, while the top was allowed to rotate on a u-joint type of connection (double pin). The specimens were held in the jaws through horizontally displaced teeth. The upper jaw of these teeth rotated along the same axis or plane as the sample, while the lower jaw rotated perpendicular to the axis of the sample, as shown in Figure 4.10. Some pre-loading of the specimens occurred during the tightening of the jaws, but it could normally be controlled to less than 10 percent of the total final load placed on the specimen.

The gripping jaws of this apparatus were located in a temperature-controlled chamber. This allowed specimens to be tested at temperatures of 2°C, 23°C, to 44°C. The specimens were placed in either an oven at 44°C or a refrigerator at 2°C, approximately one-half hour prior to the test. The specimens were moved to the temperature controlled chamber and were opened for the 5 to 10 minutes that it took to attach the LVDTs to the specimen and fit it into the jaws of the test machine. After attaching the specimen to the test device the chamber was closed and the temperature

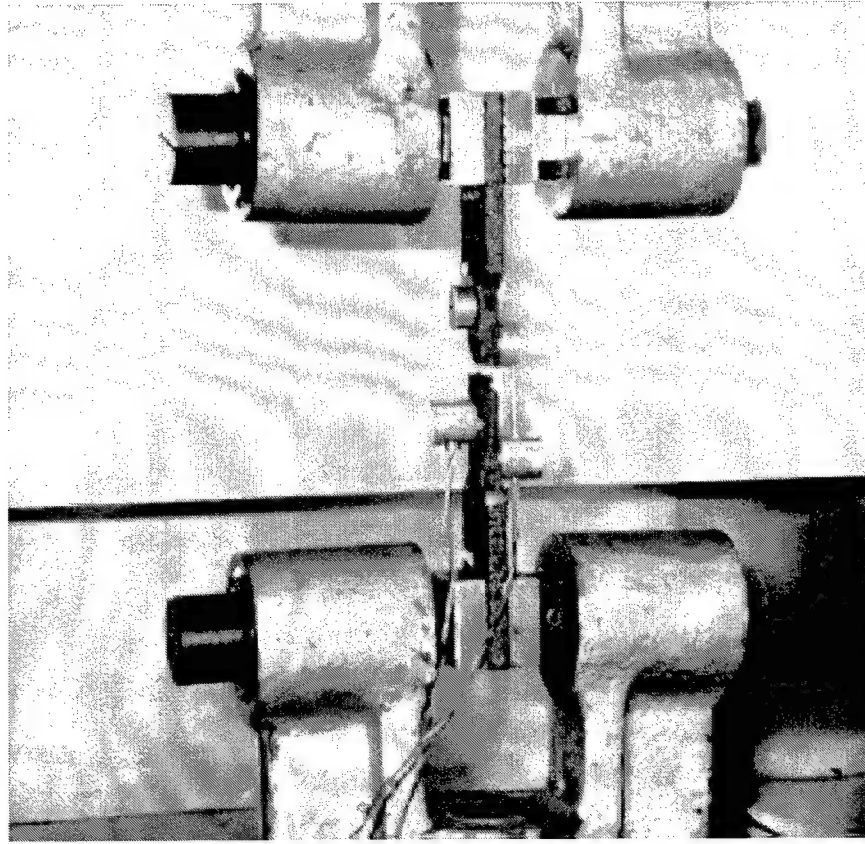


Figure 4.10 Specimen, loaded to failure in uniaxial test, LVDTs still attached.

was allowed to return to the desired level for at least 10 minutes prior to performing the test.

A program was written which would control the loading and automatically obtain measurements as required. Load and displacement values developed during a test were gathered and stored in the attached computer. The hydraulic actuators of the loading machine were controlled by displacement. The amount of load was not controlled although it was measured and recorded.

The displacement of the specimens during testing was measured through the use of linear variable displacement transducers (LVDTs). An LVDT was placed on

both sides of the specimens during testing to assure accurate displacement measurements and to detect any bending or non-axial loading that might take place. The two LVDTs also provided increased assurance that failure would occur between the transducers and that if one failed results would still be obtained. The LVDTs were attached to the specimens through the use of small brass buttons to which the LVDT equipment could be attached, Figure 4.11. These brass buttons were attached to the specimens with a silicone adhesive sealant. Experimentation showed that this black silicone material was sufficiently cured within one hour to hold the buttons in place. Generally, the buttons were allowed to cure from 2 to 16 hours (overnight) prior to testing. During the course of testing, none of these brass buttons came loose.

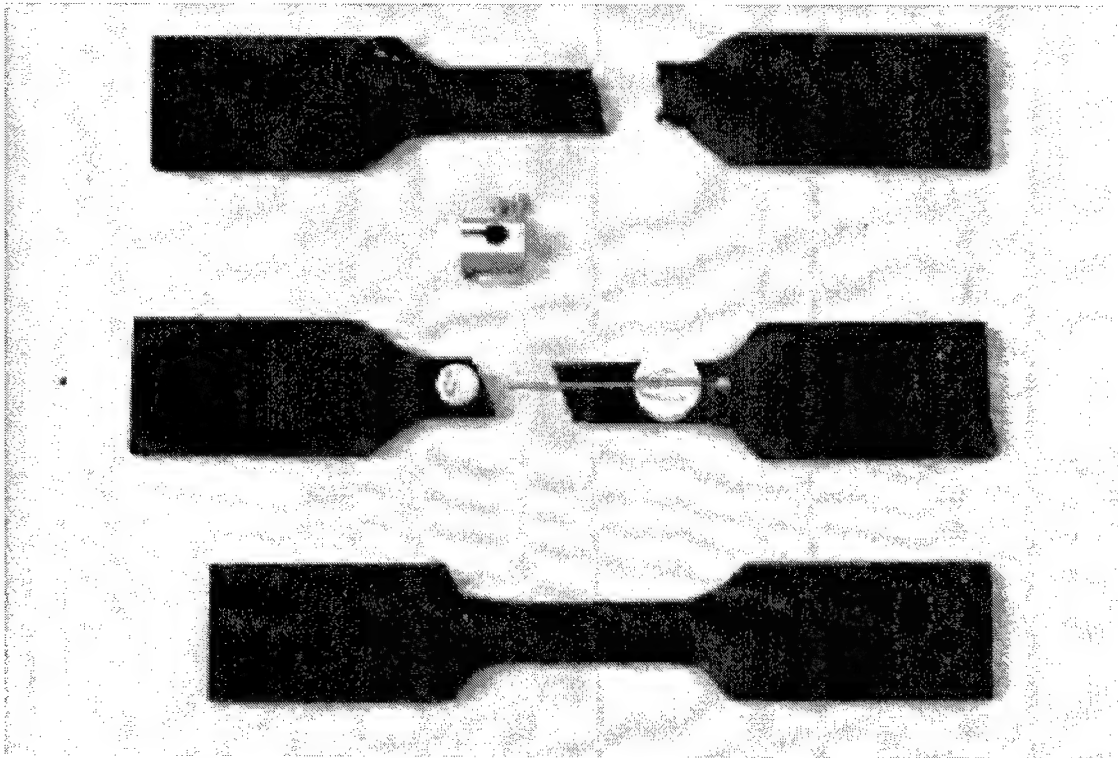


Figure 4.11 Top and middle show specimens after testing, middle specimen has brass buttons and LVDT still attached. Bottom is a specimen prior to testing.

Stress-strain evaluation. The stress and strain values obtained from a uniaxial tension test are dependent upon rate of strain. Initially, a series of uniaxial-tension tests were run at various displacement rates, to determine an appropriate rate of loading. Several mixtures were selected for this initial testing; including both modified and unmodified coal tar with low and high amounts of aggregate. The intent was to load the samples at a relatively slow rate, but at one that would not allow for an excessive amount of relaxation. This was accomplished by performing, at room temperature, a series of uniaxial tensile tests on similar samples at various rates of loading. The fastest rate of displacement that would still result the highest amount of axial load was selected as the strain rate for all tests. A rate of displacement of 0.33 mm (0.013 in.) per second was selected and used for all uniaxial tension tests. The test specimens generally reached their maximum load in from 1.5 to 7 seconds, with the polymer modified mixtures requiring the longer times. The loading rate was also analyzed on specimens tested at the low- and high-test temperatures of 2°C and 44°C (5°F and 111°F). Figures 4.10 and 4.11 show specimens that have been loaded to failure in the uniaxial tension test.

Stress-relaxation evaluation. The stress-relaxation tests were performed using the same set-up as used for the uniaxial tension tests. The controlling computer program was modified to stop the displacement at a selected location during the test and this displacement was held for two minutes while load measurements were made throughout the test.

The intent was to displace the test specimens to a point where the load applied somewhere between 40 and 50 percent of the maximum load obtained for a

comparable mixture specimen during the uniaxial tension test. The application of a set loading was not possible, as the machine was controlled by displacement and the resultant load could only be controlled indirectly. The displacement was controlled by stopping movement at one of the 430 points available along a haversine-loading curve. Because the load actuator was rated at 4,535 kg (10,000 lb) and the loads applied were much less, exact control of the load was not possible. Despite this difficulty, the loads applied were within 40 ± 5 percent of the maximum uniaxial tension load desired. The loading anomaly that occurred during the uniaxial tension tests was not detected during the stress-relaxation tests. The loads achieved may have been below the level at which the anomaly would occur.

Specimen Preparation

Coal tar emulsions are different in composition from most other bituminous emulsions in that they are colloid-type emulsion systems. Colloid systems use a clay stabilizer to hold the binder in suspension with water. Most asphalt emulsions are produced with the use of emulsifying agents without another stabilizer. Emulsifying agents are not specifically required for coal tar emulsions, although they are generally used by most emulsion manufacturers. The result of these two different emulsification processes is that the coal tar binder material cannot be readily recovered from the emulsion system after curing, because it is combined with a substantial amount of clay. Because of the clay, after curing, the cured coal tar will not liquefy when heated, as would a typical asphalt emulsion. This property of coal tar emulsions results in difficulties when preparing specimens of the material for laboratory evaluation.

Specimens of coal tar emulsion could not be cast to the exact desired shape and size required for a particular test method; therefore, large flat samples were cast and individual specimens were cut to the desired shape and size. A procedure was developed of casting large thin samples on sheets of polyethylene sheeting, as previously detailed in Chapter 3. Individual specimens were prepared from the large samples by cutting them to the desired shape with a various types of saws.

The specimens for evaluation with the bending beam rheometer (BBR) were obtained using a concrete table saw to cut specimens that were approximately 12 mm (0.5 in.) wide. The length of the specimens varied with the sample, as the uneven edges of the formed samples were cut back 6 to 12 mm (0.25 to 0.5 in.) and the remaining length varied from 125 to 150 mm (5 to 6 in.). The specimens for the direct tension and the stress-relaxation testing required additional shaping or cutting besides obtaining a rectangular section. These tests required a dog-bone shaped specimen to allow for proper testing. This dog-bone shape was attained using a thin blade (0.5 mm) precision saw to make equally spaced cuts along the test or thinner portion of the dog-bone specimens, see Figure 4.12. These cuts were not made through the complete thickness of the cured coal tar, but cuts were made from both sides in an attempt to negate the effect of the cuts on the test specimen. The excess part of the dog-bone specimens was then removed by sawing with a small hand coping saw, Figure 4.13.

The test specimens used for the uniaxial tension and stress/relaxation tests were classified as either laboratory (lab) cured or field cured. The lab-cured specimens, after fabrication, were generally cured for two to three weeks under

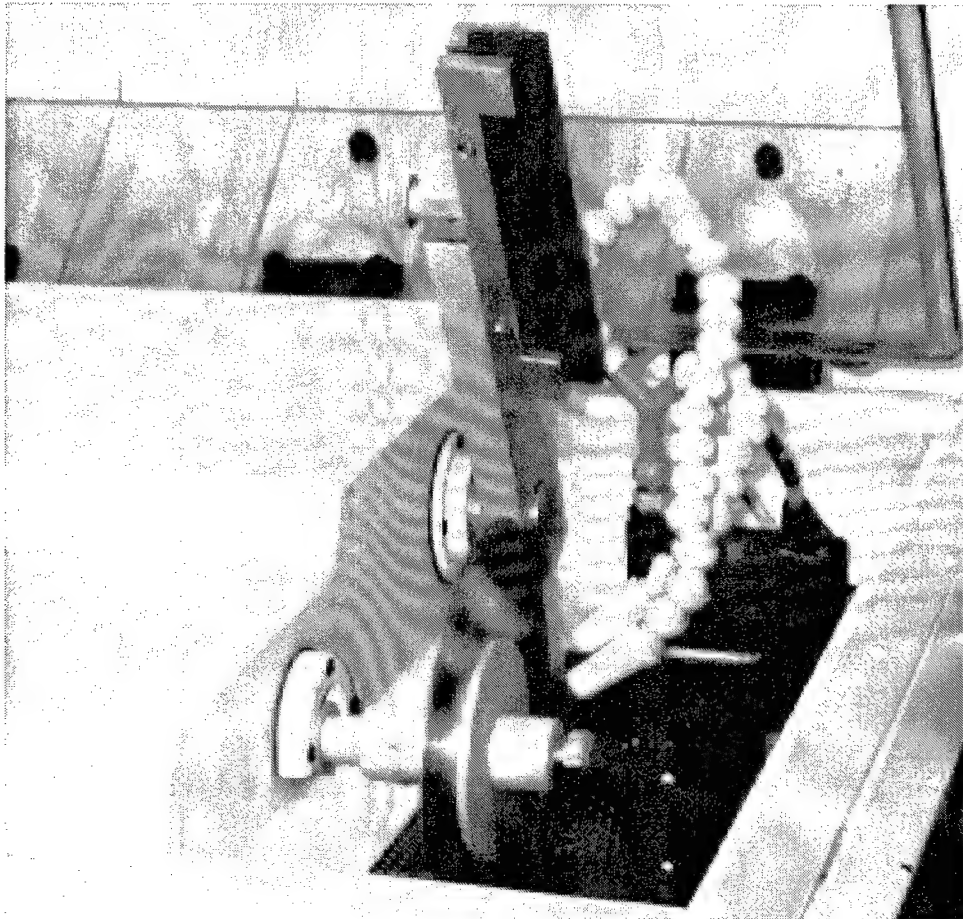


Figure 4.12 Precision saw for making parallel cuts in sealer specimens

standard laboratory conditions, prior to testing. Field-cured specimens were after a short period of lab curing, placed outside for 6 to 8 months, prior to testing.

Laboratory Curing and Aging Properties

Coal-tar emulsion, because it is an emulsion, has an initial cure wherein the water from the emulsion evaporates. This moisture loss normally occurs within 1 to 24 hours, depending on climatic conditions. After this initial weight loss, due to water evaporation, coal tar specimens will continue to loose weight, generally at a decreasing rate. This additional weight loss can be attributed to the evaporation of volatiles, as detailed in Chapter 2. This type of weight loss was much slower than the

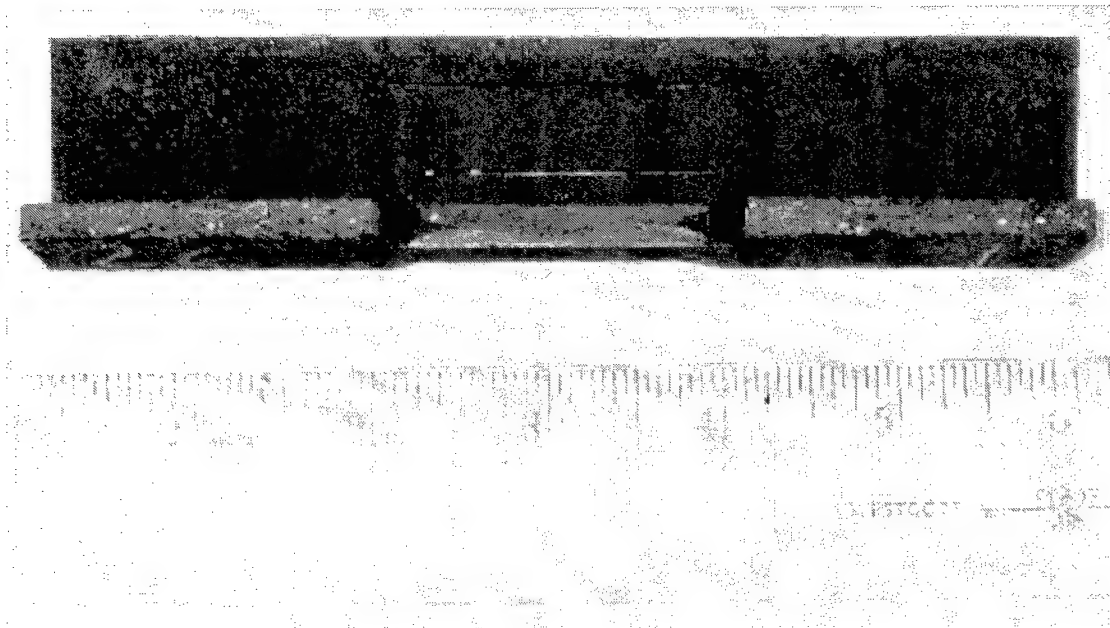


Figure 4.13 Specimens, after saw cuts (top) and sawing for dog-bone shape (bottom) – Note: effect of saw cutting from both sides with 150 mm (6 in.) diameter blade.

loss due to water evaporation and could be considered to be part of the aging process. Test specimens, prepared from larger cast samples of various mixtures, were weighed over an extended period of time and the mass of each was recorded. Specimens of various sizes and dimensions were evaluated over long periods of time and the changes in mass and in some cases specimen dimensions were recorded.

To evaluate the long-term aging process, several methods of oven curing of coal-tar mixtures were conducted. The tensile and stress-relaxation properties of various mixtures were evaluated during the selected aging process and compared to those of field-cured samples.

THERMAL PROPERTIES

The thermal properties of the cured coal tar emulsion sealer depend upon the thermal properties of the individual materials in the sealer. These individual materials

include the coal tar and clay in the emulsion and the aggregate added to the sealer mixture. Coal tar is more temperature susceptible than asphalt cement in that it has a greater change in viscosity for a given range of temperature. Emulsifying coal tar greatly reduces its temperature susceptibility so that after curing, even at high temperatures, the cured sealer will not flow. The only significant difference between a coal tar (RT-12) and a coal-tar emulsion after it has cured is the addition of the clay material. The coal-tar sealer and the underlying asphalt concrete pavement will tend to expand and contract with temperature changes relative to the thermal coefficient of their respective materials. These movements are on a relatively small scale; however, any differences in the thermal coefficients between the coal tar sealer and the underlying asphalt concrete pavement, to which the coal tar is bonded, can lead to cracking from thermally caused movements.

Research on both coal tar materials (Hoiberg 1966a) and asphalt cements (Hoiber 1966b and Janoo, et al 1995) have shown that there are temperatures where the thermal coefficient of expansion undergoes noticeable changes in value. This temperature, where the material changes from a liquid to a solid, is referred to as the glass transition temperature. Coal tar materials have been shown to pass through this glassy state somewhere between 60 and 100 °C (140 and 212 °F) below the softening point as determined in ASTM D 36 (Hoiberg 1966a). Asphalt cements generally go through a glass transition state at approximately -20°C (-4°F). Because of this, most studies on the thermal properties of bituminous materials have concentrated on the lower temperature properties in the range of 20 to -40°C (68 to -40°F). The given

glass transition temperature for both coal tar and asphalt cement will vary several degrees depending upon the source and type or grade of the material.

The coal tar emulsions evaluated in this study were made using a RT-12 grade of road tar. The current ASTM standard D 633 (Road Tar) gives a coefficient of thermal expansion per degree C of 3.0×10^{-4} for a RT 12 road tar. In 1966, the same ASTM standard used a value of 4.7×10^{-4} and other sources available from the same time frame, gave similar values (Hoiberg 1966). The ASTM standard requirements had not changed within this time frame and the reasons for the variation are not known. The softening points, as determined by ASTM D 36, of the standard base RT-12s supplied by the two manufacturers were 38.5°C (99.5°F) for manufacturer 1 and 43°C (109.4°F) for manufacturer 2. Therefore, according to Hoibert, the glass transition temperature of the RT-12s would range between approximately -19°C (-2.2°F) to -59°C (-74.2°F) (Hoibert 1966a).

Aggregates

The thermal properties of aggregates are substantially different from those of the binder materials used in both sealers and hot-mix asphalt. Generally, most aggregates used in pavement construction have coefficients of thermal expansion that are one or two orders of magnitude less than coal tar or asphalt cement. For example, the coefficients of thermal expansion for limestone and quartzite are $6 \times 10^{-6}/^{\circ}\text{C}$ and 11 to $13 \times 10^{-6}/^{\circ}\text{C}$, respectively (Mindess and Young 1981). This lower coefficient of thermal expansion has the effect that, with all other things being equal, mixtures with greater amounts of binder should have more expansion or contraction with changes in temperature.

Coal-Tar Sealer Mixtures

Thermal tests were conducted to determine the coefficient of thermal expansion for various coal tar sealer mixtures. The sealer mixtures, even those with the higher amounts of aggregate, have a relatively large volume of coal tar (binder) versus aggregate in relation to hot-mix asphalt mixtures. Therefore, the coefficient of thermal expansion of the coal tar should have a greater effect on the overall thermal properties, when compared with asphalt in hot-mix asphalt. The various coal-tar mixtures were never exposed to temperatures approaching the glass transition temperature during the laboratory thermal evaluation or during the field exposure evaluation.

The same LVDTs that were used in the uniaxial tension tests were used to determine the change in length of the coal-tar sealer mixture specimens with changes in temperature. The specimens tested were small and weighed only approximately 8 g (0.018 lb). An LVDT was affixed to the specimens using the same procedure as used for the uniaxial tension tests. As with those tests, the gage length between the two ends of the LVDT to the nearest 1/100 of a millimeter was determined using a digital caliper. In order to provide access for air flow around the specimens during the test and to allow for movement, the specimens were placed across a series of straws that were confined within a piece of Plexiglas and held down with a metal bar, see Figure 4.14.

Coal-tar emulsions are made up, by weight, of approximately 33 percent coal tar, 17 percent clay, and 50 percent water. The amount of emulsifier in the emulsion is less than 0.1 of 1 percent of the weight of the emulsion. For the plain coal-tar sealer mixture with a low aggregate loading (0.48 kg (4 lb) of aggregate per liter (gal) of coal

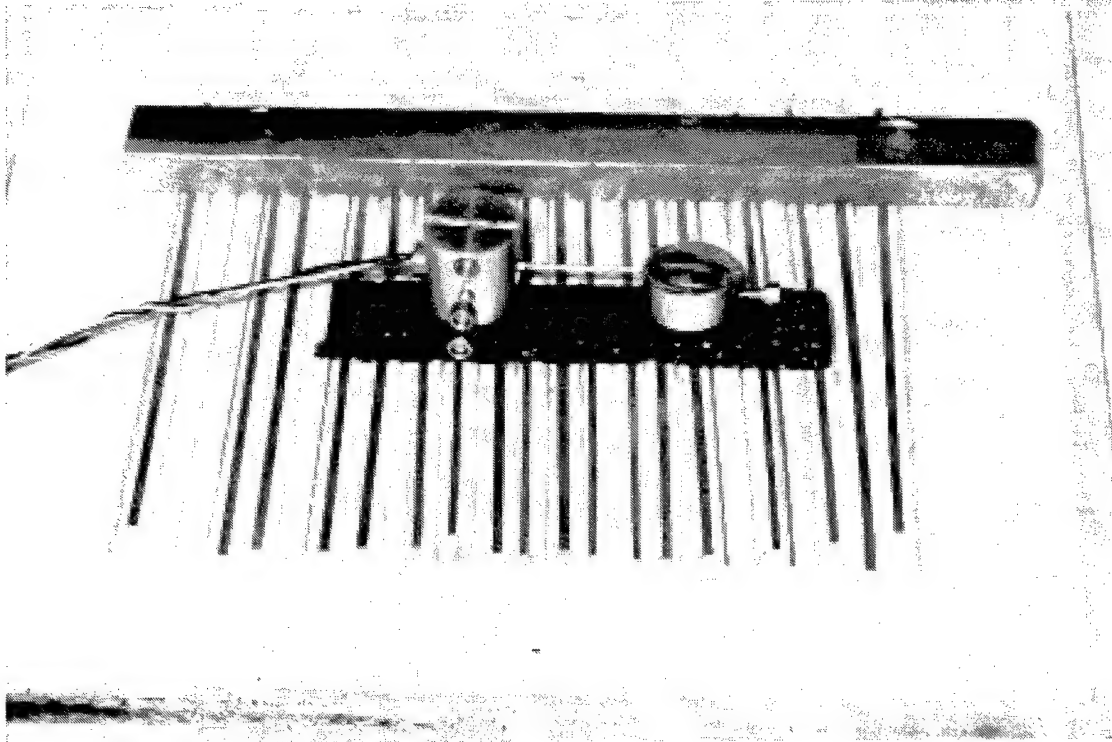


Figure 4.14 Setup for thermal evaluation of sealer specimen.

tar emulsion), the volume of materials becomes approximately 24 percent coal tar, 5.5 percent clay, 58 percent water, and 13 percent aggregate. These volume percentages are based on specific gravity values of 1.2 for the coal tar and 2.65 for the clay (Terzaghi, Peck, and Mesri 1996). After the emulsion has cured the volume of the material became approximately 56 percent coal tar, 13 percent clay, and 31 percent aggregate. Plain coal-tar mixtures with the larger amounts of aggregate (1.2 kg (10 lb) of aggregate per liter (gallon) of coal-tar emulsion) have the resulting material volumes of approximately 38 percent coal tar, 9 percent clay, and 53 percent aggregate. The effect of the latex additives on these percentages was negligible due to the relatively small amounts used when compared to the other materials.

The test procedure began with the monitored specimen at room temperature, 23°C. The temperature was then dropped in three approximately equal stages until 2°C was reached. The temperature was held constant for one-half hour at each of these points and displacement values were recorded on a constant basis. The procedure was reversed and values recorded as the specimen was brought back to the starting temperature. The same procedure was used to go from 23°C to 44°C and back to 23°C.

Underlying Hot-Mix Asphalt Pavement

The underlying hot-mix asphalt pavement was designed around the Federal Aviation Administration's (FAA's) P 401 guide specification. The materials and properties of the mixture were given in the previous chapter. The mix had an asphalt content of 4.7 percent by weight of total mixture that would comprise about 11.5 percent by volume of the hot-mix asphalt. By comparison, the volume of binder material in the sealer would be 3 to 5 times larger than the binder in the underlying hot-mix asphalt. A comparison of the coefficient of thermal expansion of both the coal tar and the asphalt cement show that the coal tar has a higher value and therefore should have greater movement with comparative changes in temperature.

ASTM D 4311 (Asphalt) gives a coefficient of thermal expansion per degree C of 3.5×10^{-4} based upon the density of the asphalt cement (density $>0.966 \text{ kg/m}^3$ at 15°C). Other sources report an asphalt coefficient of thermal expansion per degree C of 6.0×10^{-4} at temperatures of -22.5°C (-8.5°F) and above and 1.8×10^{-4} at temperatures below -22.5°C (-8.5°F) (Hoiberg 1966b). Other researchers have also

found the glass transition temperature of various hot-mix asphalt mixtures to be about -20°C (Schmidt and Santucci 1966 and Janoo, et al. 1995).

A sample of the hot-mix asphalt pavement, located next to coal tar sealer mixture number seven, was removed with a concrete saw and pry bars. The sample removed was approximately $300 \times 400 \text{ mm}$ ($12 \times 16 \text{ in.}$) in area and was removed the full depth of the 65 mm (2.5 in.) surface layer. From this sample a total of four beam specimens were cut. These measured roughly $57 \times 57 \text{ mm}$ ($2.25 \times 2.25 \text{ in.}$) square and 280 mm (11 in.) long. The original pavement surface remained un-sawed. Each beam was evaluated for thermal movement using a commercially available comparator, Figure 4.15. Metal gage studs were epoxied into the approximately center

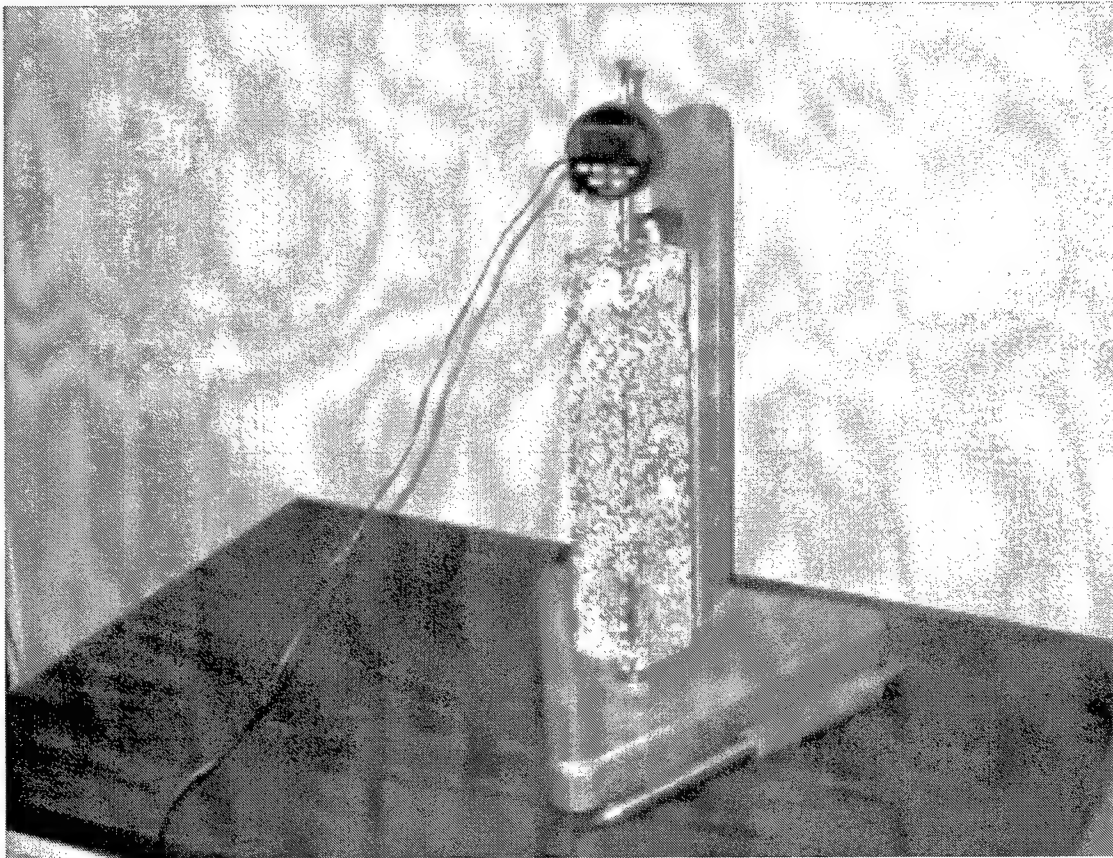


Figure 4.15 Hot-mix asphalt beam specimen in length comparator.

of the end of each beam. These studs provided reference points on each beam for the measurement of variations in length during changes in temperature.

The specimens were exposed to temperatures ranging from -22°C (-7.6°F) to 10°C (50°F) and the changes in length were measured at each of these temperatures. The upper limit of 10°C (50°F) was established through experimentation with one of the beams. At higher temperatures the specimen had a measurable creep when placed in the comparator. The lower temperature limit was selected to keep the specimens above the glass-transition temperature of the asphalt.

SUMMARY

The laboratory evaluation of the coal tar materials and mixtures included methods that are currently used within the sealer industry and several non-conventional methods. The test methods conventionally used included fuel resistance, viscosity, and freeze-thaw. The non-conventional test methods included bending beam rheometer, dynamic shear rheometer, and uniaxial tension. The evaluation also investigated the thermal properties of both the various coal-tar mixtures and the underlying hot-mix asphalt.

The evaluation of many of these parameters required the fabrication of test specimens of coal-tar mixture. The fabrication included the saw cutting of larger mixture samples into individual specimens that could be used for testing purposes. The final size of the individual specimens had to be determined through measurements with a digital caliper.

CHAPTER 5: RESULTS

CONVENTIONAL EVALUATION RESULTS

Fuel Resistance

As discussed in Chapter 2, it is acknowledged throughout the sealer industry that increasing the amount of aggregate in a mixture above a certain level will make it pervious to fuel and other fluids. The coal-tar emulsions and polymer additives supplied by both manufacturers were used to evaluate the fuel resistance of various mixtures. Tests were run on comparable mixtures 1 through 6 and 13 through 18, as defined in Table 3.5. The results of this testing showed that at 0.48 kg of aggregate per liter (4 lb of aggregate per gallon) of coal tar emulsion the sealer is impermeable to kerosene when the mixtures contain polymer, Table 5.1. The mixtures without polymer allowed at least some infiltration of kerosene through the seal coat, although it was relatively minor, Figure 4.2. The mixtures containing 1.2 kg of aggregate per liter (10 lb of aggregate per gallon) of coal-tar emulsion the sealer all failed the fuel resistance test.

To more closely evaluate the effect of polymer and aggregate on fuel resistance, various combinations of polymer and aggregate contents were evaluated for fuel resistance. The amount of aggregate was increased in 0.12 kg of aggregate per liter (1 lb of aggregate per gallon) increments. The amount of aggregate ranged from 0.24 to 0.72 kg of aggregate per liter (2 to 6 lb of aggregate per gallon) of coal-tar emulsion for the mixtures tested. The results in Table 5.2 show that a polymer additive can increase the amount of aggregate that can be added to a mixture without losing fuel resistance. Overall, the results showed that mixtures without a polymer

Table 5.1 Relationship of Various Mixtures to Resistance to Kerosene				
Sample ¹ Number	Mass Per Liter (Gallon) of Coal-Tar Emulsion			Performance ² : P- Pass, PF- Partial Failure, F- Fail
	Water, %	Additive, %	Aggregate, kg (lb)	
1	20	---	0.48 (4)	PF
13				PF
2	20	---	1.2 (10)	F
14				F
3	35	3	0.48 (4)	P
15				P
4	35	3	1.2 (10)	F
16				F
5	50	7	0.48 (4)	P
17				P
6	50	7	1.2 (10)	F
18				F

¹ Each sample represents the average result of 3 test specimens.

² Passing signifies no loss of kerosene, partial failure signifies some discoloration of the bottom of the tile – 25 to 75 mm (1 to 3 in.) in diameter, and failure indicates that all the kerosene penetrated the coating within 24 hours.

should contain no more than 0.36 kg of aggregate per liter (3 lb of aggregate per gallon) of coal-tar emulsion. For the addition of up to 7 percent polymer, the maximum evaluated in this study, this additional aggregate increased from 0.36 to 0.60 kg of aggregate per liter (3 to 5 lb of aggregate per gallon) of coal-tar emulsion.

Viscosity

Test results for the plain coal-tar emulsions and the various mixtures are given in Table 5.3. Shook (Shook et al. 1989) obtained viscosity values ranging from 56 to 153 poises for five different plain coal-tar emulsions. The values obtained for the two coal-tar emulsions used in this study were 69 and 90 poises, which fall within the above range of values. Shook (Shook et al. 1989) proposed a range of 10 to 90 poises for mixtures of coal-tar emulsion, water, aggregate, and an additive (if used). The values obtained for field test section mixtures 1 through 6 and 13 through 18, varied

Table 5.2 Relationship of Amount of Polymer and Aggregate to Resistance to Kerosene				
Sample ¹ Number	Mass Per Liter (Gallon) of Coal-Tar Emulsion			Performance ² : P- Pass, PF- Partial Failure, F- Fail
	Water, %	Additive, %	Aggregate, kg (lb)	
A	20	---	0.24 (2)	P
B	20	---	0.36 (3)	P
C	20	---	0.48 (4)	PF
D	20	---	0.60 (5)	F
E	35	3	0.24 (2)	P
F	35	3	0.36 (3)	P
G	35	3	0.48 (4)	P
H	35	3	0.60 (5)	PF
I	35	3	0.72 (6)	F
J	50	7	0.24 (2)	P
K	50	7	0.36 (3)	P
L	50	7	0.48 (4)	P
M	50	7	0.60 (5)	P
N	50	7	0.72 (6)	PF
O	50	7	0.84 (7)	F
¹ Each sample represents the average result of 3 test specimens.				
² Passing signifies no loss of kerosene, partial failure signifies some discoloration of the bottom of the tile – 25 to 75 mm (1 to 3 in.) in diameter, and failure indicates that all the kerosene penetrated the coating within 24 hours.				

from 19 to 84 poises and fall within the range proposed by Shook. Shook (Shook et al. 1989) specified that the viscosity readings should be taken immediately at the start of each test. The reason for using the initial viscosity reading is shown in Table 5.3. The viscosity readings taken after four minutes for both plain coal tar and coal-tar mixtures showed a decrease in viscosity with time, indicating thixotropic behavior. However, coal-tar mixtures are slow-flowing materials, that tend to “channel” (push the material aside), and rotational viscometers, such as the Brookfield, tend to cut a circular section from the mixture thereby resulting in decreased viscosity values with time and apparent thixotropic behavior. Therefore, the use of initial readings was adopted to avoid any error due to test timing. The

Table 5.3 Results of Viscosity Tests on Various Coal-Tar Mixtures			
Mixture Components ¹ , Plain Coal Tar Plus	Coal Tar from Manufacturer No.1/No. 2		
	Comparable Mixture No.	Viscosity (Poises)	
		Initial	After 4 minutes
No Additives	N/A	69/90	58/75
10% Water	N/A	---/66	---/56
20% Water	N/A	---/40	---/35
4# Agg. + 10% Water	N/A	19/---	18.5/---
4# Agg. + 20% Water	1/13	19/35	17/33
4# Agg. + 30% Water	N/A	---/24	---/22
10# Agg. + 10% Water	N/A	68/---	49/---
10# Agg. + 20% Water	2/14	55/---	44/---
10# Agg. + 30% Water	N/A	34/---	26/---
4# Agg. + 35% Water + 3% Polymer	3/15	25/84	16/46
10# Agg. + 35% Water + 3% Polymer	4/16	40/---	22/---
4# Agg. + 50% Water + 7% Polymer	5/17	26/56	21/17
10# Agg. + 50% Water + 7% Polymer	6/18	60/67	34/36
¹ All component amounts given are based on 1 gallon of coal-tar emulsion.			

Brookfield viscometer test results were obtained at a speed of 20 RPM with a No. 27 spindle.

Freeze-Thaw

Initial tests, using the PCTC procedure (Sebaaly et al. 1999), provided results showing the relative order of mixture performance from best to worst was 5, 6, 15, and 17, Table 5.4. These results generally match the field performance of these mixtures, except that in the field mixture 15 performed worse than mixture 17, Table 3.7.

Mixtures 15 and 17 were made with a coal-tar emulsion and polymer from a different manufacturer than the other two mixtures. These mixtures exhibited some surface imperfections within a few days after placement and these were more severe in the mixture with greater amounts of polymer (No. 17), Figure 5.1. The imperfections were slight tears in the surface and the cause was not known. Similar imperfections

Table 5.4 Results of PCTC Freeze-Thaw Tests ¹ on Various Coal-Tar Mixtures				
Mixture/ Specimen Number	Crack Rating ²		Surface After 10 Cycles	
	5 Cycles	10 Cycles	Maximum Crack Width (mm)	Percentage of Area Cracked
5/1	0	0	N/A	0
5/2	0	0	N/A	0
6/1	1	2	0.15	9
6/2	2	3	0.20	12
15/1 ³	3	4	0.50	27
15/2 ³	3	4	0.35	21
17/1 ³	4	4	0.85	40
17/2 ³	4	4	0.80	38
¹ After Sebaaly et al. 1994				
² Rating scale is as follows: 0 – No cracking, 1 – Hairline cracking, 2 - Slight cracking, 3 - Moderate cracking, and 4 – Severe cracking, see Appendix for criteria.				
³ Mixtures contained some surface tears after curing.				

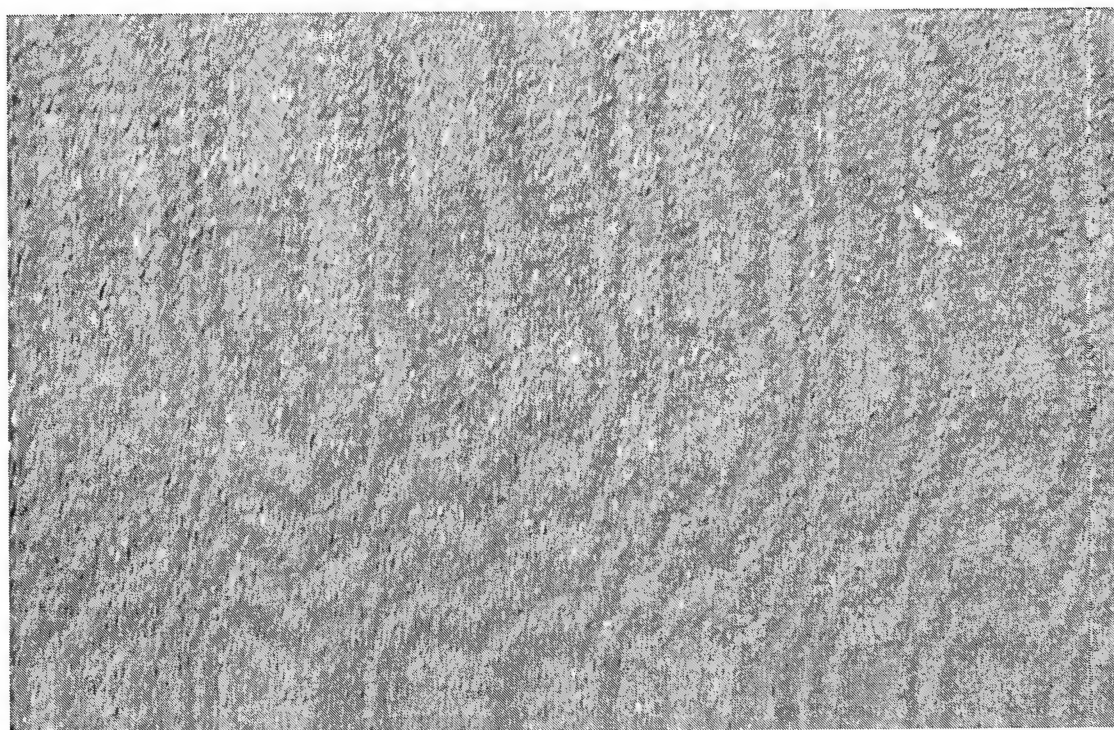
were noted in the test specimens of mixture 17 prior to the start of the freeze-thaw test.

The fabrication of specimens for the freeze-thaw test provides a good opportunity to observe the overall compatibility of the sealer mixtures components. Specimens that develop any distress during curing will probably develop similar distresses in field application.

An evaluation of a 24-hour test procedure developed in this study provided results similar to those obtained with the PCTC procedure, Table 5.5. Mixtures 3, 5, and 6 performed the best, which was indicative of what occurred in the field. The results of these tests and field results as given in Table 3.7 were used to develop the rating system, as given in Table 5.5 and Appendix C. Considering the field performance of the mixtures, the rating system developed was able to properly indicate the relative performance of the various mixtures. Mixtures 15, 16, and 17 all exhibited the surface same surface imperfections or tears that occurred in similar



(a)



(b)

Figure 5.1 Surface imperfections that appeared in mixtures containing polymer, (a) worst of imperfections, 8 to 14 mm (mixture 17), (b) typical surface with a few imperfections (mixture 15).

Table 5.5 Results of Alternative Freeze-Thaw Tests ¹ on Various Coal-Tar Mixtures				
Mixture/ Specimen Number	Values After 5/10 Cycles			
	Max. Crack Width (mm)	Percentage of Area Cracked	Crack Severity Value ²	Crack Rating ³
1/1	0.15/0.15	7/43	1.1/6.45	2/4
1/2	0.15/0.20	9/45	1.4/9.0	2/5
3/1	0.15/0.15	4/8	0.6/1.2	1/2
3/2	---/---	0/0	0/0	0/0
5/1	0.30/0.40	3/5	0.9/2.0	1/2
5/2	0.30/0.33	6/9	1.8/2.7	2/2
6/1	0.20/0.25	7/10	1.4/2.5	2/2
6/2	0.15/0.20	16/24	2.4/4.8	2/3
13/1	0.20/0.25	10/27	2.0/6.8	2/4
13/2	0.20/0.20	9/22	1.8/4.4	2/4
15/1 ⁴	0.40/0.45	13/20	5.2/9.0	4/5
15/2 ⁴	0.40/0.40	12/15	4.8/6.0	3/4
16/1 ⁵	0.40/0.45	13/16	5.2/7.2	4/4
16/2 ⁵	0.33/0.45	10/13	3.3/5.9	3/4
17/1 ⁵	0.40/0.55	17/19	6.8/10.5	4/5
17/2 ⁵	0.30/0.35	11/13	3.3/4.6	3/3
¹ Corps of Engineers test procedure given in appendix ² Value = Maximum crack width x Percentage of area cracked ³ Rating scale is as follows: 0 – No cracking, 1 – Slight cracking, 2 – Low cracking, 3 – Moderate cracking, 4 – Heavy cracking, and 5 – Severe cracking. Value given is average value; see Appendix for method and criteria. ⁴ Mixtures contained some minor surface tears after curing, questionable for evaluation. ⁵ Mixtures contained numerous surface tears after curing – specimens not acceptable for freeze-thaw evaluation.				

mixtures for the PCTC procedure. As before, these imperfections increased with increasing amounts of polymer in the mixture. The modified test procedure is much easier to perform and monitor than the PCTC procedure because while it allows testing operations to be performed on a consistent daily basis, it also allows for a shorter overall testing time frame and interruptions over non-working periods such as weekends and holidays. The procedure uses relatively more high temperature than freezing conditioning because of the aging process of coal tar materials. The

wet-freezing cycle is used only for thermal movements and the high temperature conditioning is used to age the mixture.

One benefit available from the freeze-thaw test that is not directly tied to the testing method employed, is an overall assessment of the compatibility of the sealers components. Placement of the various coal-tar sealer mixtures containing coal-tar emulsion from manufacturer No. 2 illustrated what appeared to be some kind of compatibility problem between this manufacturers emulsion and polymer additive. The specimens fabricated for this test are much larger in area than those of any other test, which provides a better opportunity to observe performance. Imperfections that form during freeze-thaw test specimen fabrication appear to provide an indication of field performance.

NON-CONVENTIONAL EVALUATION RESULTS

Bending Beam Rheometer

BBR tests were conducted on various mixtures with and without aggregate. The initial testing was conducted on specimens without aggregate. This testing involved varying the amount of polymer in the specimens. Table 5.6 provides the results of BBR testing on these specimens and their age at testing. Figure 5.2 shows the same data as a plot of creep stiffness versus time of cure. These results show that the creep stiffness of the coal-tar mixtures increased with time, while approaching an asymptotic value. For this coal-tar emulsion, the amount of polymer additive in the mixture did not have a substantial effect on creep stiffness. However, the creep stiffness was initially somewhat greater in specimens without polymer and the long-term results showed a slight decrease in creep stiffness with increasing amounts of polymer.

Table 5.6 BBR Test Results on Cured Coal-Tar Emulsion With Various Amounts of Polymer						
Specimen No.	Amount of Polymer, %	Creep Stiffness Values, MPa, at -6°C and 60 Seconds Time				
		Mean/COV ¹ (Days of Specimen Laboratory Cure ²)				
1	0	219/0.46 (6)	752.3/6.43 (34)	1182.5 ³ (103)	1380/6.19 (371)	1483/28.4 (1,165)
2	3	282/10.5 (17)	644/6.56 (43)	967.6/12.7 (107)	1160/5.71 (354)	1550/16.9 (1,149)
3	5	433.5/2.78 (23)	759/6.03 (56)	1036.4/4.6 (100)	1180/3.28 (347)	1462/4.28 (1,142)
4	8	552/3.44 (27)	---	953.2/2.93 (96)	1096/2.63 (343)	1600/4.24 (1,138)

¹ Coefficient of Variation = Standard Deviation/Mean x 100.
² Time in days from the day the specimens were cast until they were tested.
³ Average of two specimens (1182 and 1183)

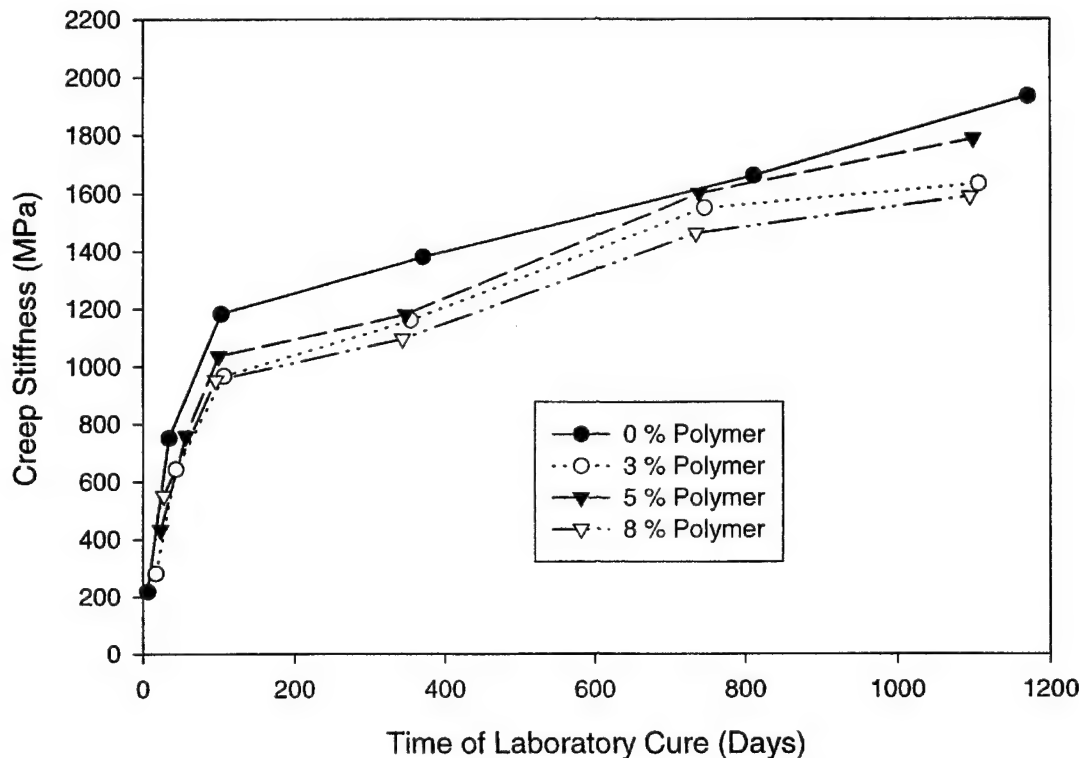


Figure 5.2 Effect of amount of polymer on creep stiffness versus time, coal-tar emulsion from manufacturer No. 1.

The BBR test was also run on aged and non-aged samples of mixtures 1 through 6 and on aged mixtures 14, 16, 17 and 18, as shown in Table 5.7. The non-aged (laboratory cured) specimens had been cast about three weeks prior to testing,

Table 5.7 BBR Results for Aged and Non-Aged Coal-Tar Mixtures					
Mixture Number ¹			BBR Values at 0°C (Test Time of 60 Seconds)		
Manu- facturer	Non- aged	Aged	Creep Stiffness (MPa)		
			Mean	Std. Deviation	Coef. Of Variation (COV)
No. 1	1 ²		594	19	3.20
		1	2228	197	8.84
	2 ²		718	61	8.50
		2	3034	628	20.70
	3		369	31	8.40
		3 ²	1670	196	11.74
	4		892	29	3.25
		4	1510	78	5.17
	5		302	33	10.93
		5	1572	199	12.66
	6		718	37	5.15
		6 ²	2572	552	13.35
No.2		14 ³	2570	839	33.29
		16 ³	2566	586	23.65
		17 ³	1978	223	11.52
		18 ³	2937	266	9.08
¹ Five specimens tested. ² Four specimens tested. ³ Three specimens tested.					

while the aged specimens had been field cured for about 6 to 8 months. As expected the aged mixture specimens had greater creep stiffness, when compared to non-aged samples. The consistency of the test results, as indicated by the coefficient of variation, was below 10 percent for the majority of the laboratory-cured (non-aged) mixtures, with a maximum value of 10.93 percent. The COV was larger for the aged mixtures and largest for the aged mixtures that used the coal-tar emulsion from

manufacturer No 2. A contributing factor to the relatively large variation in the results was specimens of a non-consistent or non-uniform size (cut, not molded). Due to preparation procedures required for coal-tar emulsions (Specimen Preparation, Chapter 4), each specimen had to be measured and the average dimension for width and height used to determine the stiffness with Equation 4.2.

Comparing the results from identical mixtures, except for the source of the coal-tar emulsion, the mixtures using coal tar from manufacturer No. 2 had generally greater stiffness values compared to those of the other manufacturer. The one exception was between mixtures F2 and F14, although these mixtures had COV's of 20.7 and 33.3, respectively.

A statistical analysis was conducted using SPSS software, windows version 9.0. This analysis evaluated the results from each individual test using a one-way ANOVA (analysis of variance). As part of the ANOVA analysis, a multiple comparison procedure (homogeneity of variance analysis option) was conducted using the Duncan multiple-range test, with a 95 percent confidence interval. This procedure was used for all property comparisons that follow. The comparisons are reported using the letters 'A', 'B', 'C', 'A/B', 'B/C', etc. The letter 'A' is used to rank a group with the lowest parameter value followed by the remaining letters in the appropriate order. A double letter designation, such as 'A/B', indicates that the parameter values of the mixtures in a group are not significantly different from either of the other groups 'A' or 'B'.

In this case, the multiple comparison procedure ranked the stiffness values obtained for each mixture. In the four groups of comparable samples, where the only

differences within a group were the manufacturer of the emulsion, only one pair of samples F4 and F16 showed a significant difference in the stiffness of the mixture, Figure 5.3.

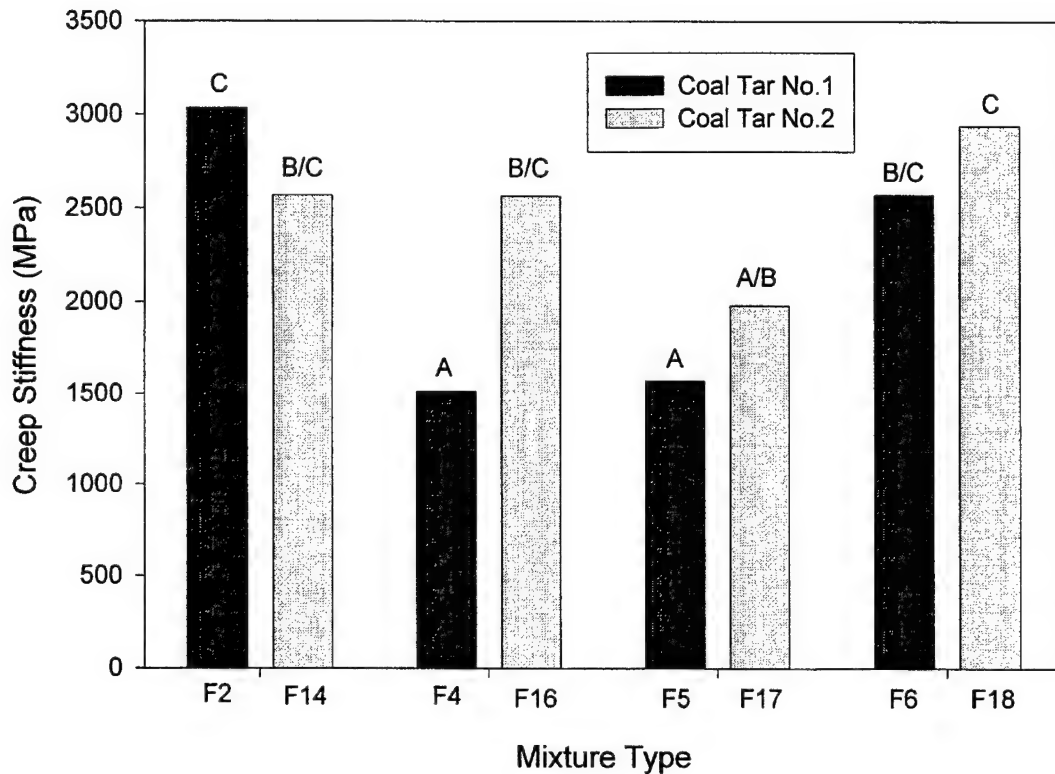


Figure 5.3 Effect of coal tar source on creep stiffness at 0°C.

Dynamic Shear Rheometer

The results of the DSR evaluation of the RT-12s from manufacturers 1 and 2 are given in Table 5.8. The temperature range over which the coal tars were evaluated was only 10°C (18°F), while most asphalt cements are evaluated over a range 2 to 3 times as large. This smaller range than what is normally used with asphalt cements was required due to the temperature susceptibility (large change in properties with a

small change in temperature) of the coal tar. The results show a measurable difference of the phase angle and the complex modulus between the two tars. The greater phase angle and lower complex modulus of the tar from manufacturer 1, at all temperatures, indicates that this tar was not as stiff as the tar from manufacturer 2.

Table 5.8

Results of DSR Testing on RT-12 Tars

Manufacturer	Temperature, C (F)	Sample No. ¹	Phase Angle (degrees)		G*, × 10 ⁵ (Pa)	
			Mean	COV ²	Mean	COV ²
No. 1	20 (68)	1	84.06	0.37	5.94	1.90
		2	86.82	0.72	6.65	1.22
		3	86.73	1.24	7.13	3.09
		Avg.	85.87	1.82	6.57	9.08
	25 (77)	1	86.39	0.23	1.55	0
		2	87.90	0.28	1.84	0.54
		3	87.92	0.17	2.01	0.57
		Avg.	87.40	1.00	1.80	12.9
	30 (86)	1	89.21	0.028	0.387	0.54
		2	89.71	0.108	0.450	0.13
		3	89.55	0.040	0.468	0.21
		Avg.	89.49	0.285	0.435	9.83
No. 2	20 (68)	1 ³	81.30	---	26.80	---
		2	79.94	1.84	25.67	8.17
		3	83.38	1.87	24.57	5.82
		Avg.	81.54	2.13	25.68	1.12
	25 (77)	1	84.46	1.73	7.54	1.38
		2	84.69	1.38	7.38	1.56
		3	85.25	0.61	7.15	1.24
		Avg.	84.80	0.48	7.36	2.66
	30 (86)	1	87.61	0.17	1.69	0.59
		2	87.68	0.097	1.73	0.88
		3	87.44	0.080	1.63	0.94
		Avg.	87.58	0.145	1.69	2.98

¹ Each of three specimens was tested 3 times.

² Coefficient of variation (COV) = (Std. Deviation/mean) × 100.

³ Specimen 1 was tested only twice at 20°C (68°F).

Uniaxial Tension

Two different coal-tar emulsions from two different manufacturers were used in making specimens for uniaxial testing. Uniaxial tension tests were performed on both laboratory and field cured coal tar sealer mixtures and the resulting maximum loads and stress values achieved are given in Table 5.9. Tests were conducted at 23°C (73°F) and 44°C (111°F) and in some instances at 2°C (36°F). The field-cured samples of each mixture were evaluated with three specimens of each type in the uniaxial test. Problems encountered during specimen preparation and with the mechanical and computer controlled equipment during the testing, resulted in three of the mixtures having data from only two tests. One use for the results of the tension tests was to determine the load or range of load required to run the stress-relaxation tests. Performing a t-test on the loads obtained from several field and also some laboratory cured mixtures with three successful tension tests showed that the results obtained were generally not statistically different within a 95 percent degree of confidence. Therefore, in order to reduce the amount of testing, only one or two specimens of each mixture type were performed on the laboratory-cured specimens of mixtures 2, 3, 4, 5, 6, and 15.

The effects of various parameters on the uniaxial test results and in particular the stress-strain results are discussed in the following paragraphs in regards to the source of the emulsion, aggregate amounts, temperature, polymer amount, and aging. A statistical analysis, in regards to these parameters, was conducted using methods and software previously discussed for the BBR test results. The multiple comparison procedure ranked stress level obtained for each mixture at a selected strain level of 10,000 microns. This strain level was selected because it was achieved for all

Table 5.9 Results of Tensile Tests on Laboratory and Field Cured Samples							
Mixture Number	Manu- facturer	Temperature °C (°F)	Cure ¹	Maximum Tensile Load, Newtons		Maximum Stress Value ³ , kPa	
				Mean	COV ²	Mean	COV ²
1	No. 1	2 (6)	Lab	301.7	6.90	4265.0	3.39
		23 (73)	Lab	33.3	1.73	393.3	10.27
			Field	126.5 ⁴ /120.3 ⁴	—	2010 ⁴ /1844 ⁴	---
		44 (111)	Lab	12.0	16.67	130.0	15.38
			Field	58.3	6.02	826 ⁴ /905 ⁴	---
2		23 (73)	Lab	77 ⁴ /74 ⁴	---	590 ⁴ /540 ⁴	---
			Field	216.3	1.75	2206.5	4.37
		44 (111)	Lab	30 ⁴	---	290.0 ⁴	---
			Field	82.0 ⁴ /83.0 ⁴	—	898.0 ⁴ /907.0 ⁴	---
3		23 (73)	Lab	29.2 ⁴	---	400 ⁴	---
	Field		117.7	5.66	1476.3	5.33	
	44 (111)	Lab	10.9 ⁴	---	114.0 ⁴	---	
		Field	48.5	—	562 ⁴ /644 ⁴	---	
4	23 (73)	Lab	58.8 ⁴	---	990.0 ⁴	---	
		Field	115.7	1.32	1584.0	5.44	
	44 (111)	Lab	19.7 ⁴	---	290.0 ⁴	---	
		Field	78.7	2.64	826.7	13.8	
5	23 (73)	Lab	28.6 ⁴	---	375.0 ⁴	---	
		Field	140.0	5.58	2125.0	16.99	
	44 (111)	Lab	11.6 ⁴	---	177.0 ⁴	---	
		Field	58.3	1.97	620.7	9.83	
6	23 (73)	Lab	48.5 ⁴	---	445.0 ⁴	---	
		Field	224.7	2.19	2717.5	3.21	
	44 (111)	Lab	13.1 ⁴	---	98.0 ⁴	---	
		Field	83.3	3.67	844.0	7.14	
13	No. 2	2 (6)	Lab	277.3	6.01	4433.3	3.68
			Field	260 ¹	---	3350.0 ⁴	---
		23 (73)	Lab	45.0	3.03	698.3	3.60
			Field	128.7	2.50	1875.0	5.06
		44 (111)	Lab	18.5	2.50	317.3	0.79
Field			58.0	5.97	834.3	6.18	
15		2 (6)	Lab	325.0 ⁴ /--- ^{4,5}	---	5300.0 ⁴	---
		23 (73)	Lab	55.0 ⁴ /--- ^{4,5}	---	850.0 ⁴	---
			Field	151.3	10.27	2124.7	10.10
		44 (111)	Lab	19.6 ⁴ /19.2 ⁴	---	330.0 ⁴ /290.0 ⁴	---
Field	75.0	10.91	1017.3	18.78			

¹ Lab – denotes 3 to 4 weeks of curing in laboratory conditions, Field – denotes 6 to 8 months of curing under field conditions.

² Coefficient of variation (COV) = (Std. Deviation/mean) × 100.

³ Stress value at a strain of 10,000µm.

⁴ Individual test value (s).

⁵ Individual specimen test result not valid due to testing problem.

mixtures at the test temperatures of 23°C (73°F) and 44°C (111°F). Even though, a maximum strain level of about 18,000 microns was achieved with several mixtures, at 10,000 microns most mixtures were already at or near their maximum stress level.

Figure 5.4 is a typical plot of the stress versus strain for field-cured mixtures at 44°C (111°F). The field-cured specimens, identified with the prefix, F, were cured or aged in the field for 6 to 8 months as discussed in Chapter 3. The number following the letter indicates the mixture number, as given in Tables 3.5 and 5.9. The prefix, L, which appears in the following statistical analysis, identifies the specimens as laboratory-cured, aged, or cured for about 3 to 4 weeks under laboratory conditions. The specimens were subjected to a strain rate of 0.33 mm/sec (0.013 in./sec).

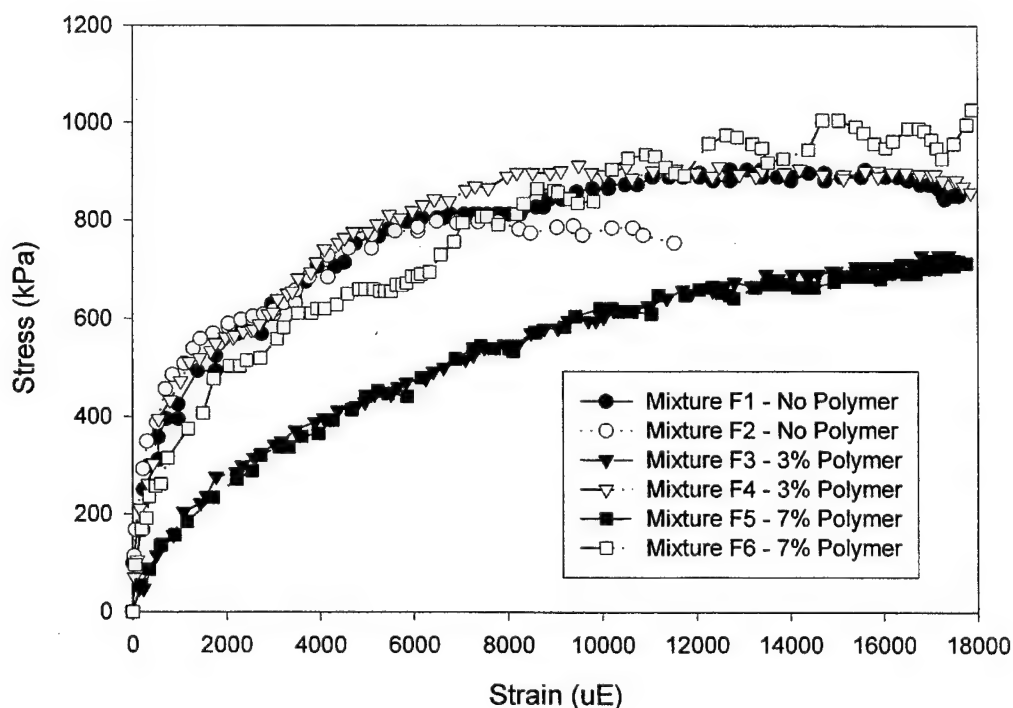


Figure 5.4 Typical plot of stress-strain results from uniaxial tension test.

Different coal-tar emulsions. The grouping analysis shown in Figure 5.5 for field cured identical (except for the source of the coal tar), mixtures, at 23°C (73°F) and 44°C (111°F), shows no statistically significant difference in the amount of stress developed between the two coal-tar emulsions. The grouping analysis of the same laboratory cured mixtures (L1/L13)), indicated a statistically significant difference in the amount of stress developed between the two coal-tar emulsion mixtures at 23°C (73°F) and 44°C (111°F), Figure 5.6.

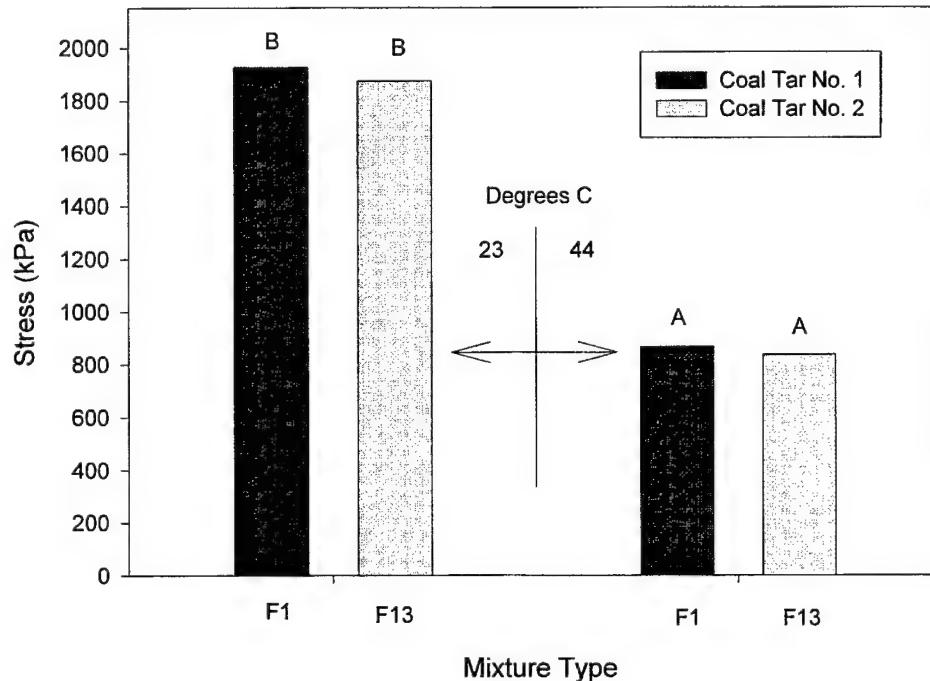


Figure 5.5. Effect of coal tar source on tensile strength (field cured).

Aggregate. At 23°C (73°F), the field cured coal-tar mixtures (F1 and F2) showed a statistically significant difference in the amount of stress developed in the uniaxial tension test, Figure 5.7. The mixture with the higher amount of aggregate

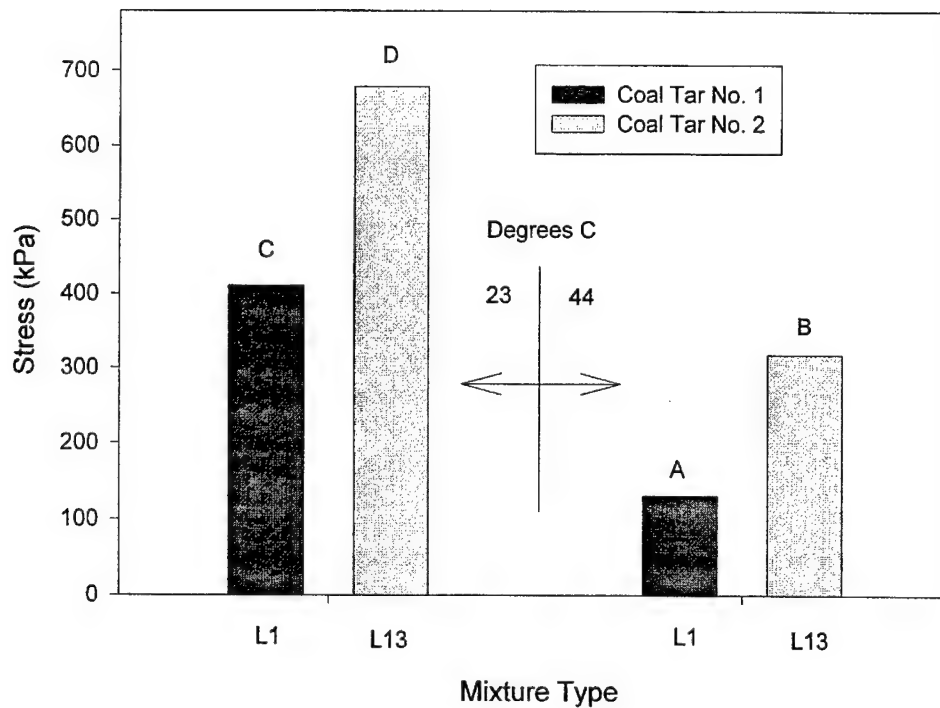


Figure 5.6 Effect of coal tar source on tensile strength (laboratory cured)

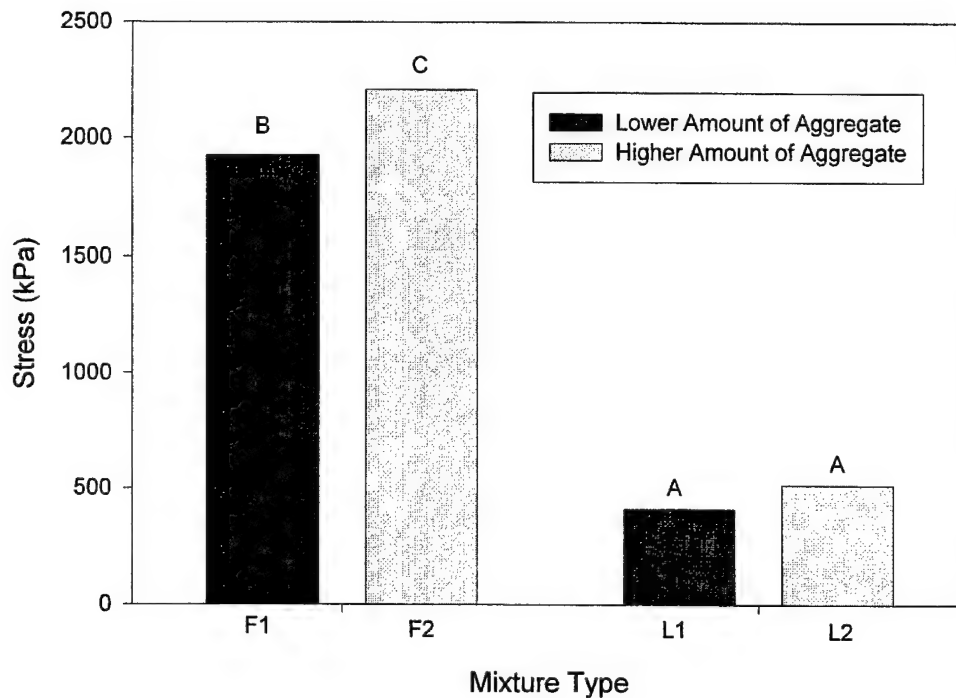


Figure 5.7 Effect of amount of aggregate on tensile strength (field (F) and laboratory (L) cured, tested at 23°C).

(F2) had a higher level of stress. The laboratory cured mixtures (L1 and L2) at 23°C (73°F) and 44°C (111°F) and the field-cured mixtures at the higher temperature did not show a statistically significant difference in the level of stress, Figure 5.7 and 5.8.

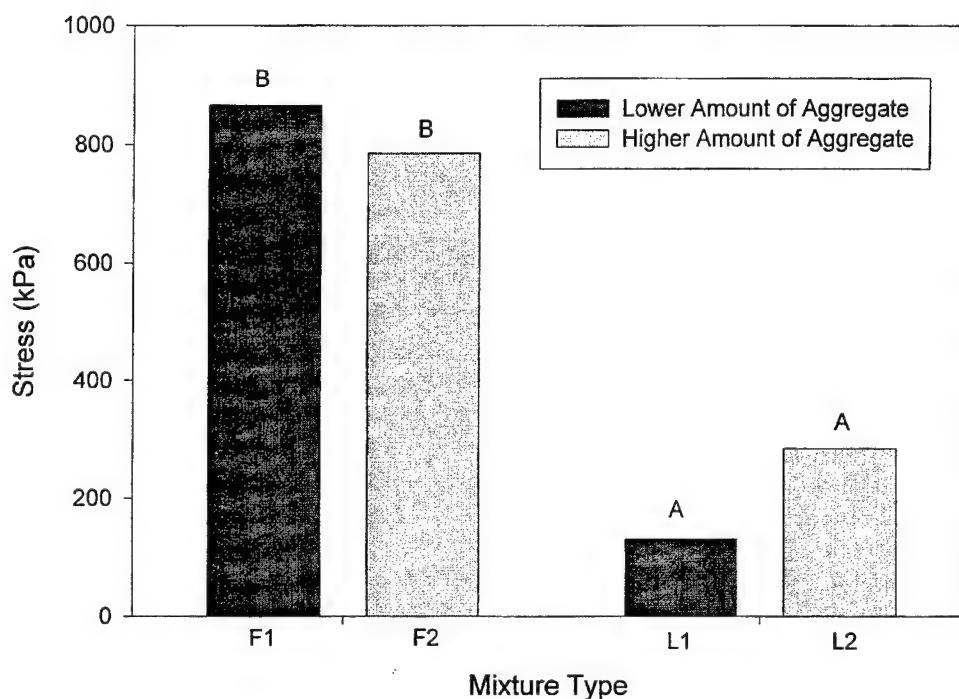


Figure 5.8 Effect of amount of aggregate on tensile strength (field (F) and laboratory (L) cured, tested at 44°C).

Temperature. Temperature, as expected, has a substantial effect on the load and stress levels obtained in uniaxial tension. A grouping analysis showed a statistically significant difference in the amount of stress developed, except for mixture L2, Figure 5.9. The stress level was lower in L2 at the higher temperature; however, the grouping analysis did not find the difference statistically significant. An increase in temperature resulted in a decrease in the stress levels attained at failure.

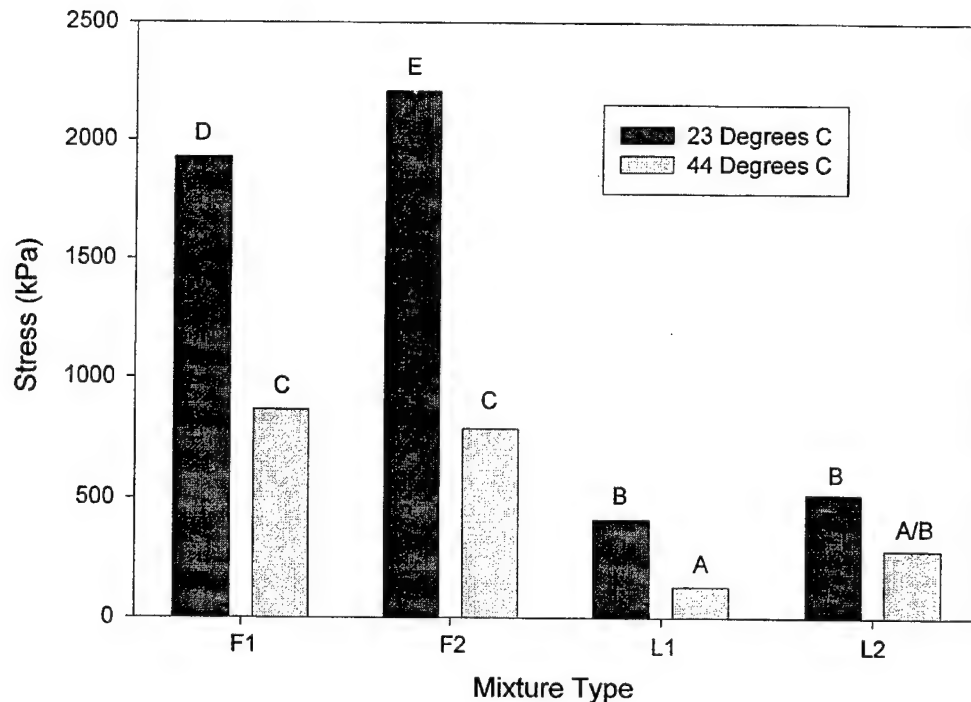


Figure 5.9 Effect of temperature on tensile strength (field (F) and laboratory (L) cured).

Polymer. The polymer in the coal-tar mixtures made the mixtures more ductile. In other words, the specimens generally reached similar load levels before failure, but they held this load or something slightly less for substantially longer periods of time (larger amounts of strain) than plain mixtures. Instead of a brittle type of failure, the polymer modified specimens deformed or necked down prior to failure. The amount of strain or time until failure increased as the amount of polymer in the mixtures increased. A grouping analysis showed a statistically significant difference in the amount of stress developed between mixtures with various amounts of polymer at 23°C (73°F), Figure 5.10. The addition of polymer to the 3 percent level resulted in a decrease in the amount stress developed, while additional polymer up to the 7 percent level increase the level of stress equal to or greater than the plain mixtures.

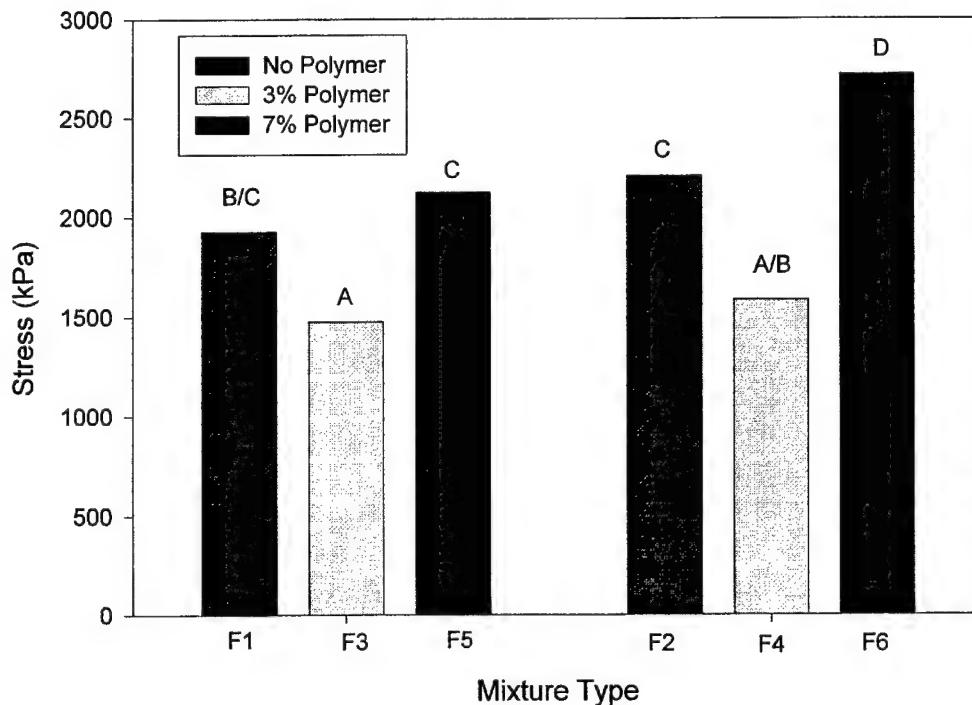


Figure 5.10 Effect of amount of polymer on tensile strength (field cured, tested at 23°C).

At 44°C (111°F), the results were not consistent, for mixtures with lower amounts of aggregate, the addition of polymer significantly reduced the amount of stress developed, Figure 5.11. However, for mixtures with higher amounts of aggregate, the addition of polymer did not significantly affect the level of stress achieved, Figure 5.11.

Aging. The term aging, as discussed in Chapter 4, refers to the curing conditions (time and/or climatic) used to prepare test specimens. These were defined as either lab or field curing, Table 5.9. The grouping analysis showed a statistically significant difference in the amount of stress developed between the lab- and the field-cured mixtures at test temperatures of 23°C (73°F) and 44°C (111°F), Figures 5.12 and 5.13.

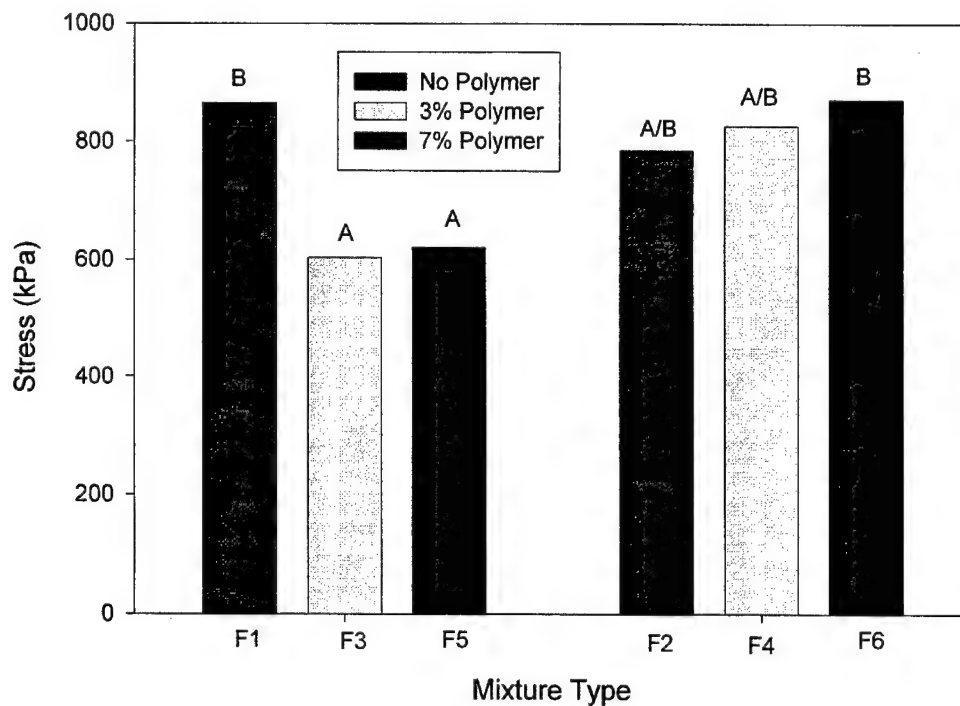


Figure 5.11 Effect of amount of polymer on tensile strength (field cured, tested at 44°C).

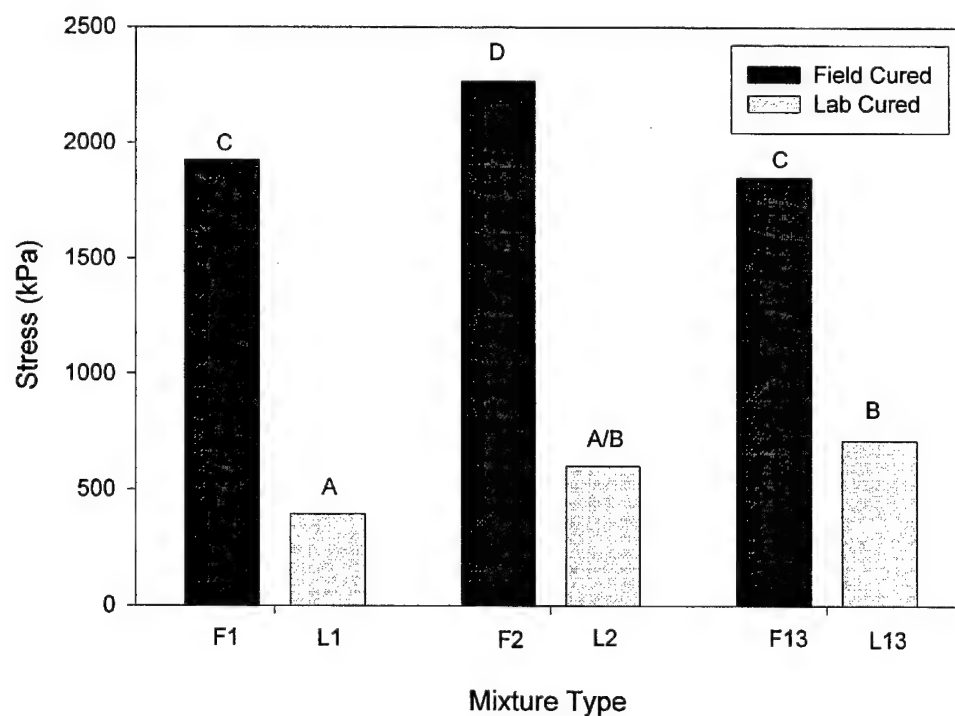


Figure 5.12 Effect of aging on tensile strength (field (F) and laboratory (L) cured, tested at 23°C).

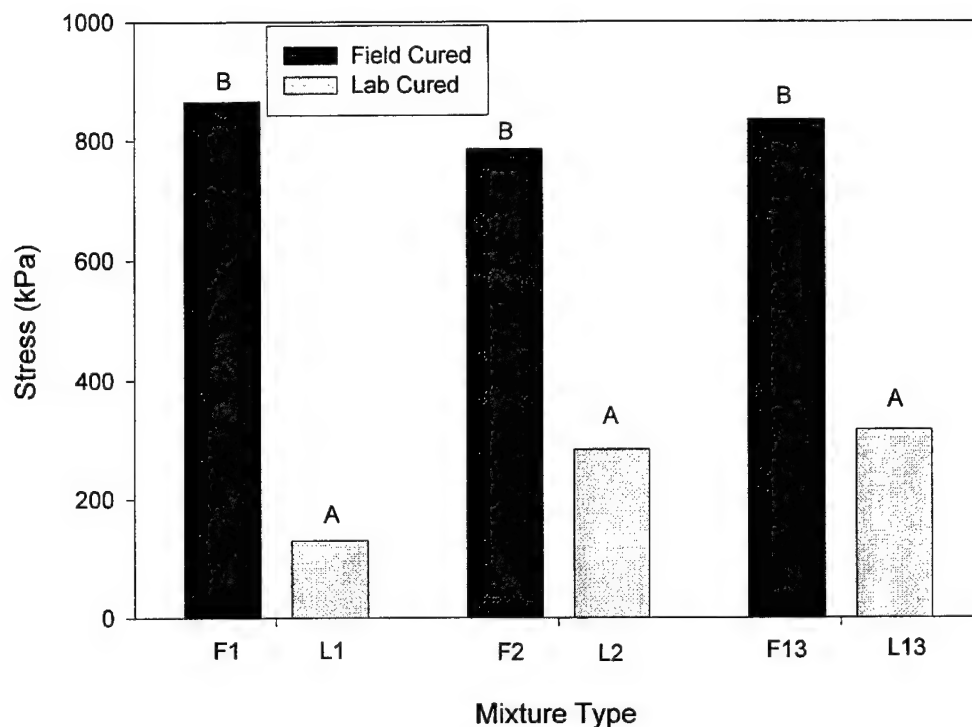


Figure 5.13 Effect of aging on tensile strength (field (F) and laboratory (L) cured, tested at 44°C).

Stress-Relaxation Test Data

Stress-relaxation tests were conducted on the same mixtures that were tested in uniaxial tension. As with the uniaxial tensile tests, the stress-relaxation tests were performed at two temperatures 23°C (73°F) and 44°C (111°F), with a few tests at 2°C (36°F).

In order to assure that the test conditions evaluated the mixtures within the range of linear viscoelastic behavior, several test mixtures were evaluated at different amounts of strain and therefore different amounts of instantaneous stress. As discussed in Chapter 2, if variations in the amount of instantaneous stress result in nearly proportional variations in strain, the material is exhibiting linear behavior. The results of the evaluation of specimens of mixtures 3, 4, and 13 tested at 23°C (73°F),

with some at 44°C (111°F), are listed in Table 5.10. The ratio of the stress to strain obtained from these tests showed comparable results between like specimens regardless of the displacement or stress imposed on the specimen. Therefore, for these mixtures, at these temperatures, the material behaved linearly.

Table 5.10 Results of Stress-Relaxation Tests of Mixtures 3, 4, and 13 at Different Temperatures to Evaluate Linear Viscoelasticity						
Mixture No.	Temperature °C(°F)	Specimen No.	Displ ¹ (mm)	Load (N)	Load Ratio ² Max/Min	Stress/strain Ratio ³ (kPa/μE) × 100
3	23 (73)	1	0.065	15.2	2.82	9.87
		2	0.050	13.0	3.17	12.44
		3	0.055	10.6	2.87	10.19
		4	0.050	8.6	3.07	8.69
4	23 (73)	1	0.065	34.2	4.17	18.54
		2	0.070	30.0	3.61	19.04
		3	0.030	29.2	3.02	
4	44 (111)	1	0.065	13.8	1.97	
		2	0.042	11.9	2.42	19.18
		3	0.018	10.8	2.45	20.60
13	23 (73)	1	0.035	27.5	2.24	31.25
		2	0.040	23.8	2.20	25.30
		3	0.032	18.7	2.53	25.63
		4	0.026	16.7	2.49	26.40

¹ Average displacement, as measured by the two LVDTs.
² The load ratio.
³ The stress/strain ratio.

Figure 5.14 shows a typical plot of normalized stress values obtained from performing the stress-relaxation tests on field-cured mixtures versus the log of the time at 44°C (111°F). The normalized stress values that are plotted are obtained by dividing each stress value determined during the test by the maximum stress first imposed; consequently, the resulting values are between 0 and 1. Similar values can be obtained using the values of load; however, the use of the computed stress value

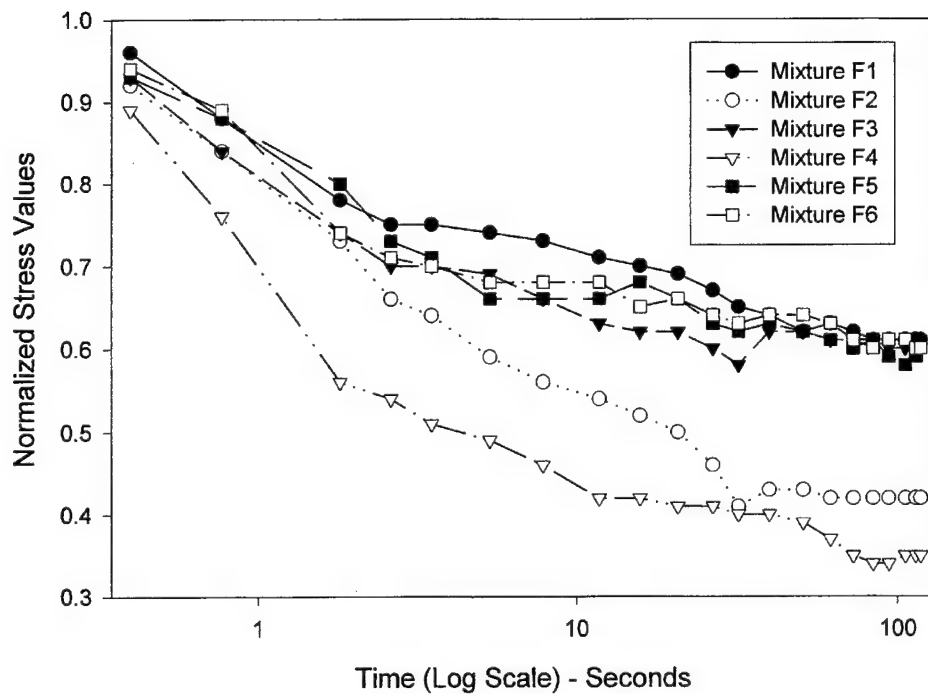


Figure 5.14. Typical plot of normalized stress values from stress-relaxation test

takes into account the variations in size of the various test specimens. As expected, the normalized stress values decreased rapidly at first followed by a more gradual rate of decrease until after about two minutes there was little additional change. To insure the time of testing was adequate, two additional laboratory-cured mixtures were strained for four minutes instead of the two-minute test interval. A grouping analysis, similar to that used for BBR test results showed that there was no statistically significant change in the normalized stress values developed by testing the mixtures for an additional two minutes.

The effects of various parameters on the stress-relaxation test results are given in the following paragraphs. These parameters include the source of the emulsion, aggregate amounts, temperature, polymer amount, and aging. As was done with the

uniaxial tension test results, the results of the stress-relaxation tests were evaluated using a statistical grouping procedure to help identify the effect of various mixture parameters.

Different Coal-Tar Emulsions. Field and laboratory cured specimens were made with coal-tar emulsions from two manufacturers, without polymer and with lower amounts of aggregate. These mixtures were evaluated for statistically significant differences in normalized stress values. A grouping analysis showed that there were no statistically significant differences in normalized stress values between field-cured mixtures at 23 °C (73 °F) and 44 °C (111 °F), Figure 5.15. A grouping analysis of laboratory-cured specimens at 23 °C (73 °F) and 44 °C (111 °F) also showed no statistical differences, Figure 5.16. The results of this analysis showed that the coal-tar emulsions behaved similarly, even at different temperatures and with different curing conditions.

Aggregate. The effect of the amount of aggregate in the mixture was evaluated by comparing mixtures whose only variation was in the amount of aggregate they contained. A grouping analysis at 23 °C (73 °F) a comparison of field and laboratory cured mixtures revealed that only the field-cured mixture with a higher amount of aggregate (F2), provided a statistically significant increase in normalized stress values, Figure 5.17. There was not a statistically significant difference between the remaining three mixtures, at this temperature. At 44 °C (111 °F), similar results were obtained except that at this temperature the field-cured mixture with a lower amount of aggregate (F1) provided a statistically significant increase in normalized stress values, Figure 5.18.

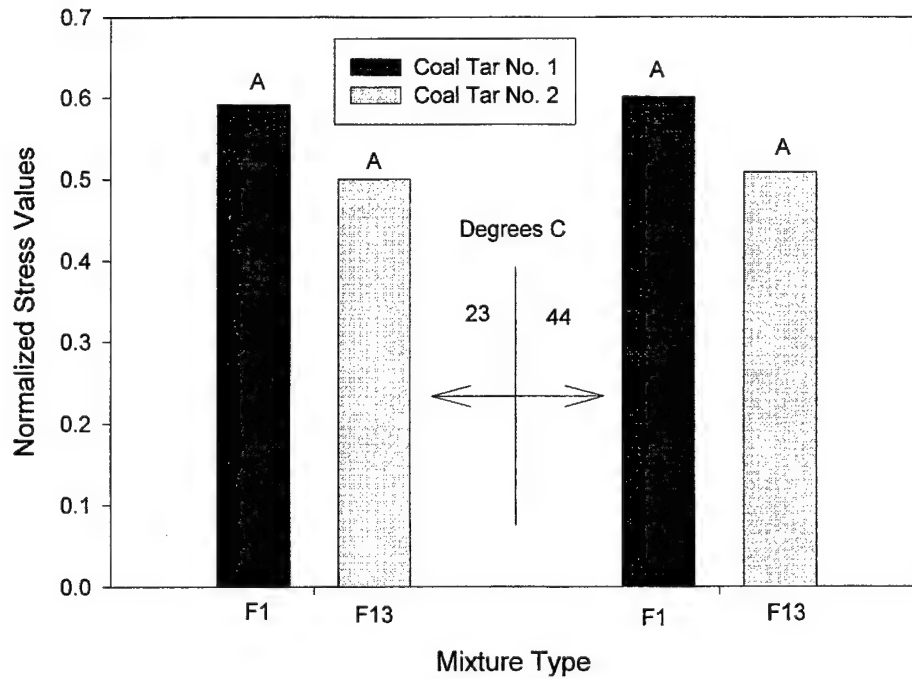


Figure 5.15 Effect of coal tar source on normalized stress values (field cured).

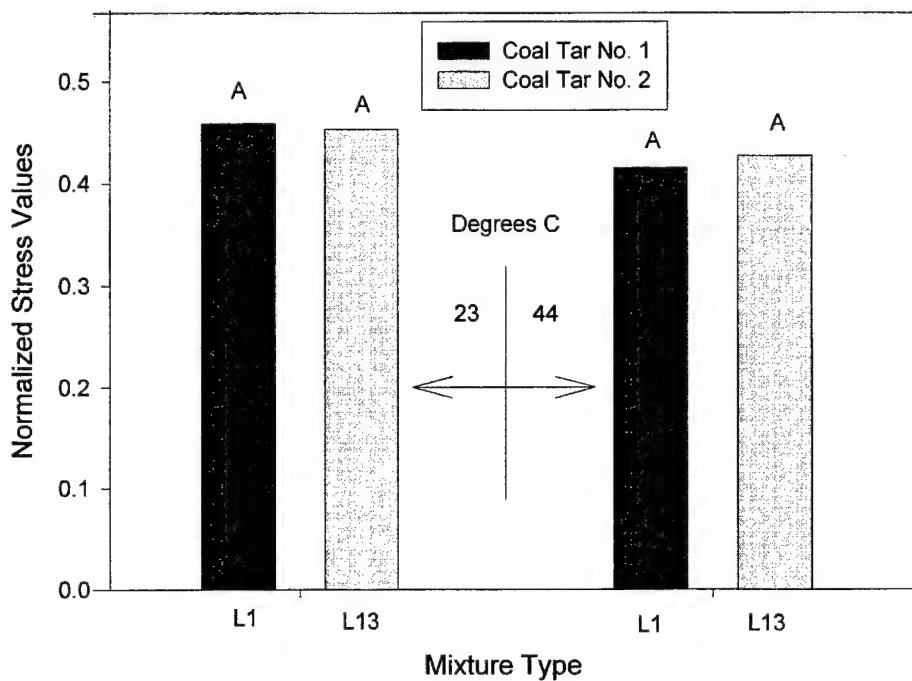


Figure 5.16 Effect of coal tar source on normalized stress values (laboratory cured).

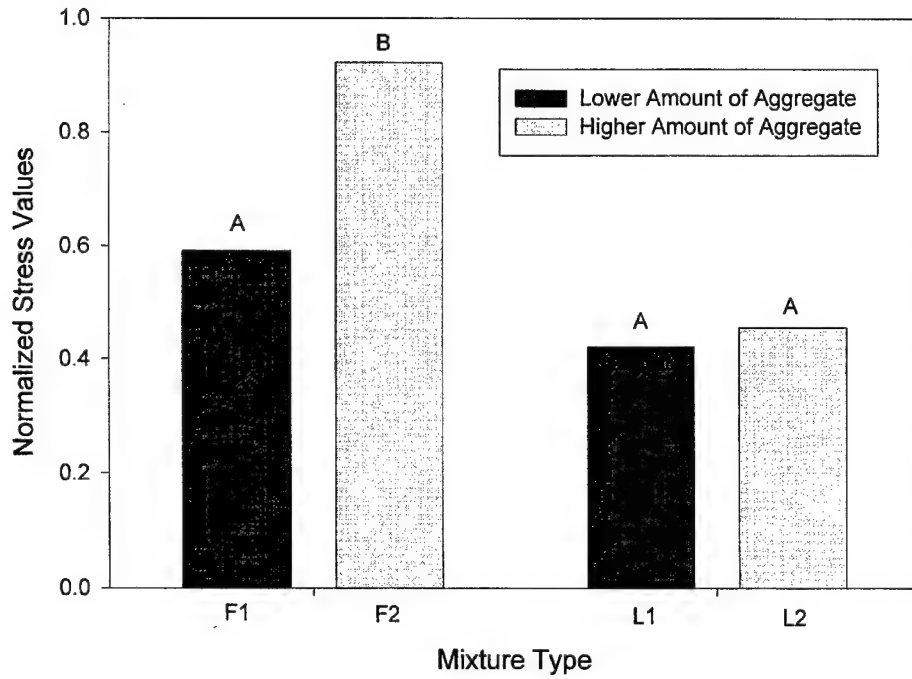


Figure 5.17 Effect of amount of aggregate on normalized stress values (field (F) and laboratory (L) cured, tested at 23°C).

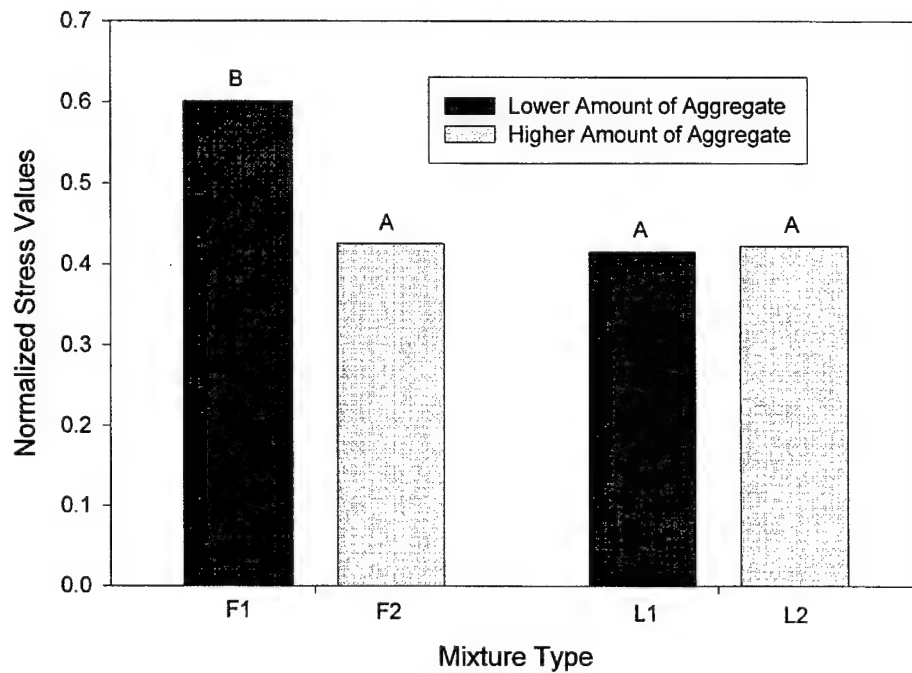


Figure 5.18 Effect of amount of aggregate on normalized stress values (field (F) and laboratory (L) cured, tested at 44°C).

Temperature. The effect of temperature on the normalized stress values were obtained from comparisons of field and laboratory cured specimens of plain (no polymer) coal-tar mixtures. Generally, the grouping analysis showed that temperature did not produce a statistically significant difference in normalized stress values, except for an increase in the higher amount of aggregate mixture (F2) at 23 °C (73 °F),

Figure 5.19.

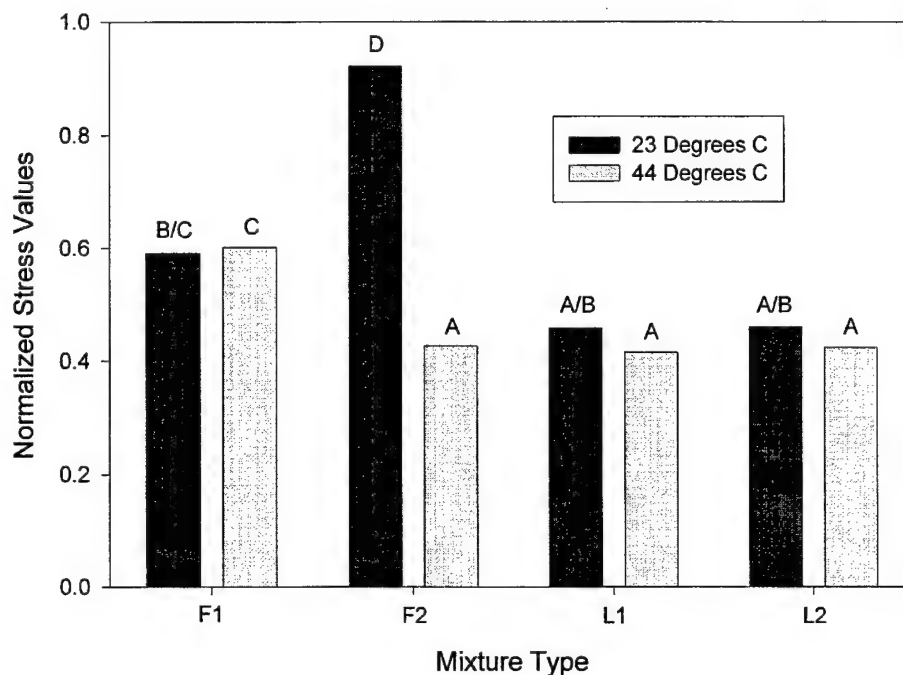


Figure 5.19 Effect of temperature on normalized stress values (field (F) and laboratory (L) cured).

Polymer. Field- and lab-cured specimens containing, zero, 3, and 7 percent polymer were evaluated at two different temperatures. At 23 °C (73 °F), a grouping analysis the field-cured specimens showed a statistically significant reduction in normalized stress values for the 3 percent polymer mixtures and for the 7 percent mixture with higher amounts of aggregate (F6), Figure 5.20. At 44 °C (111 °F), the

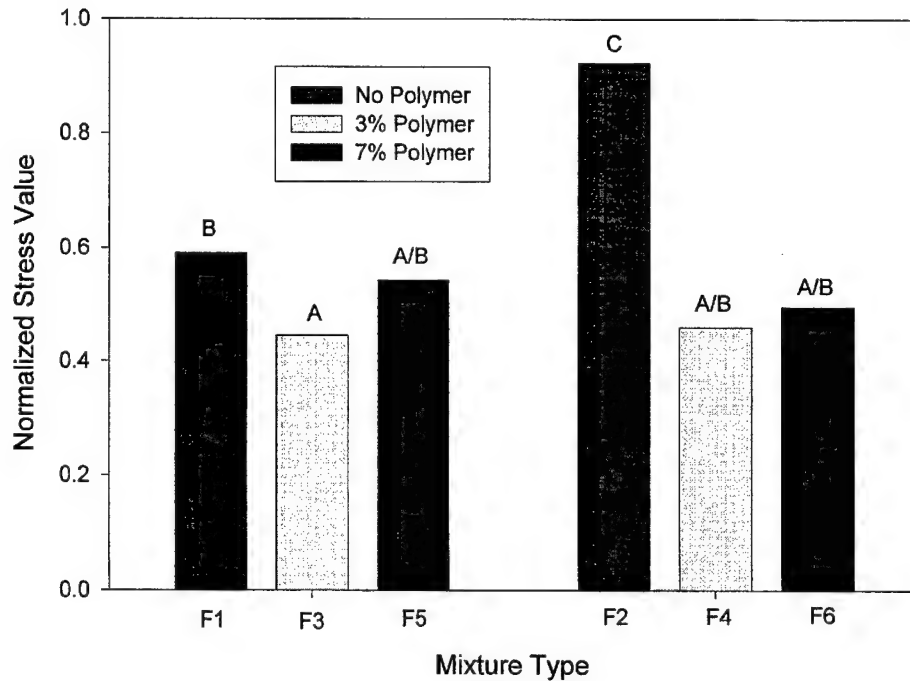


Figure 5.20 Effect of amount of polymer on normalized stress values (field cured, tested at 23°C).

field-cured specimens did not show a statistically significant difference in normalized stress values, except for an increase in the 7 percent mixture with higher amounts of aggregate (F6), Figure 5.21. The lab-cured mixtures at 23°C (73°F) showed a statistically significant reduction in normalized stress values for the addition of polymer, Figure 5.22. This reduction was greatest in mixtures containing 3 percent polymer. At 44°C (111°F), the polymer didn't have a significant effect on normalized stress values for lab-cured specimens, Figure 5.23.

Aging. Comparable plain (no polymer), high and low aggregate, field- and lab-cured specimens were evaluated at two temperatures. Coal-tar emulsions from two manufacturers were also used in making specimens. The grouping analysis showed that aging made a statistically significant difference on the normalized stress

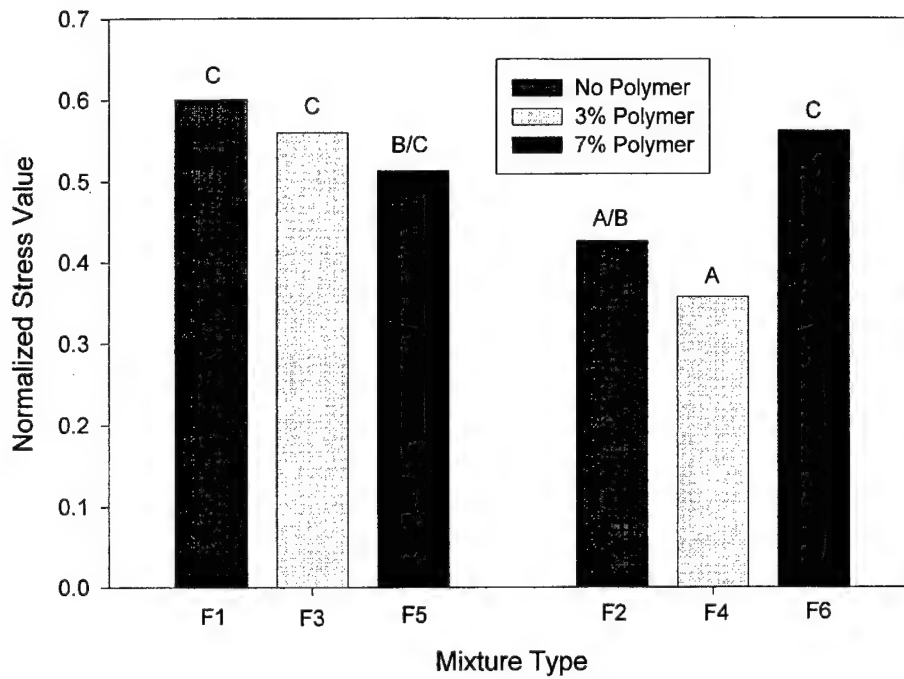


Figure 5.21 Effect of amount of polymer on normalized stress values (field cured, tested at 44°C).

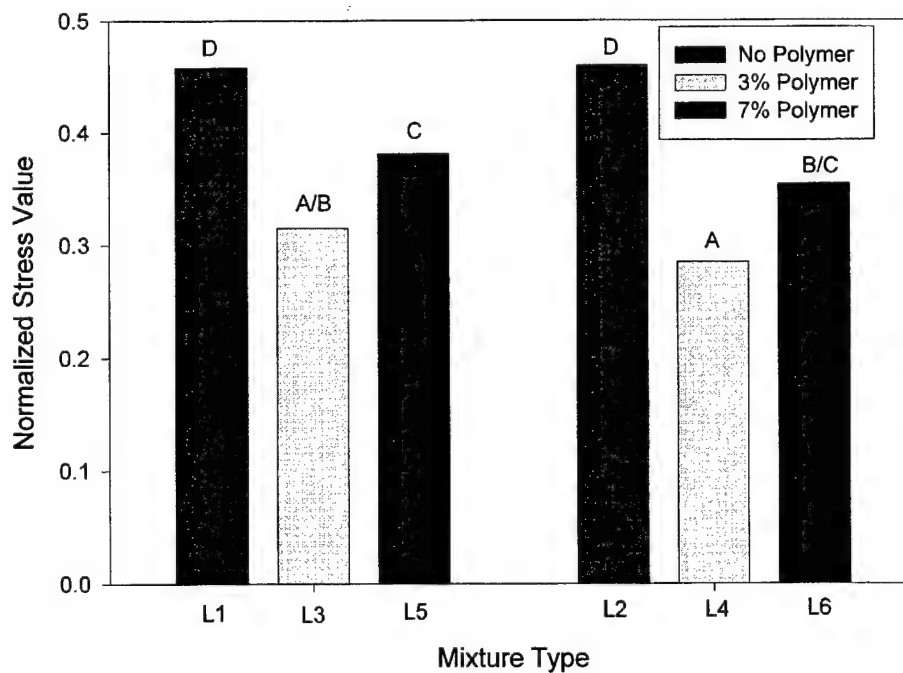


Figure 5.22 Effect of amount of polymer on normalized stress values (laboratory cured, tested at 23°C).

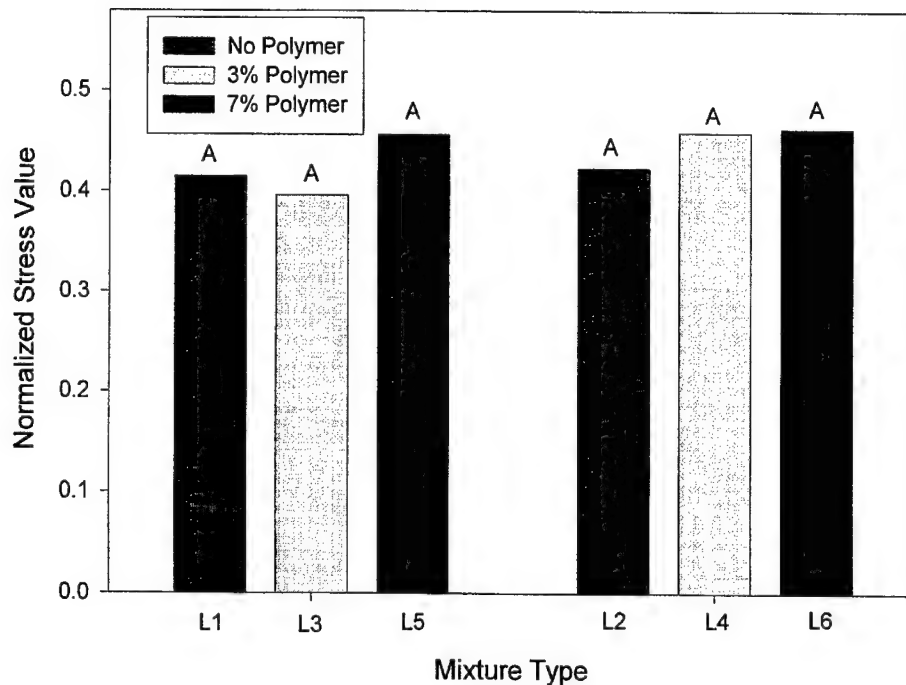


Figure 5.23 Effect of amount of polymer on normalized stress values (laboratory cured, tested at 44°C).

values of one of the three comparative mixtures at each temperature. At 23°C (73°F), the mixture from coal-tar manufacturer No. 1, with the higher amount of aggregate (F2), had a statistically significant increase in the normalized stress values, Figure 5.24. At 44°C (111°F), the mixture from coal-tar manufacturer No. 1, with the lower amount of aggregate (F1), had a statistically significant greater normalized stress value, Figure 5.25.

CURING/AGING

Curing (Mass Loss)

Coal-tar emulsion mixtures lose mass through two mechanisms after placement. The first mechanism is the loss of water from the emulsion through evaporation. The amount of water mass loss varies with the mixture evaluated, due to

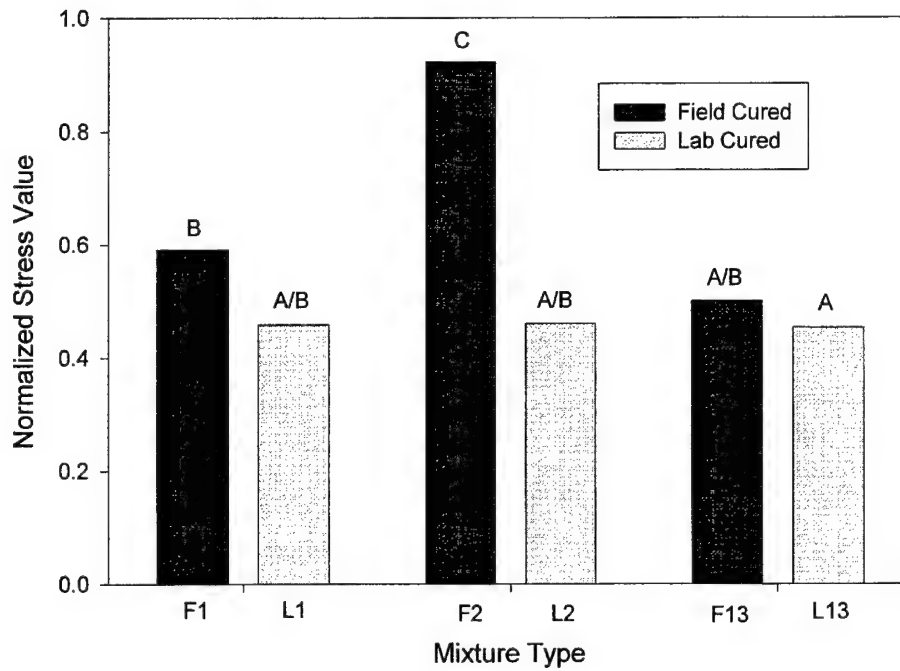


Figure 5.24 Effect of aging on normalized stress values (field (F) and laboratory (L) cured, tested at 23°C)

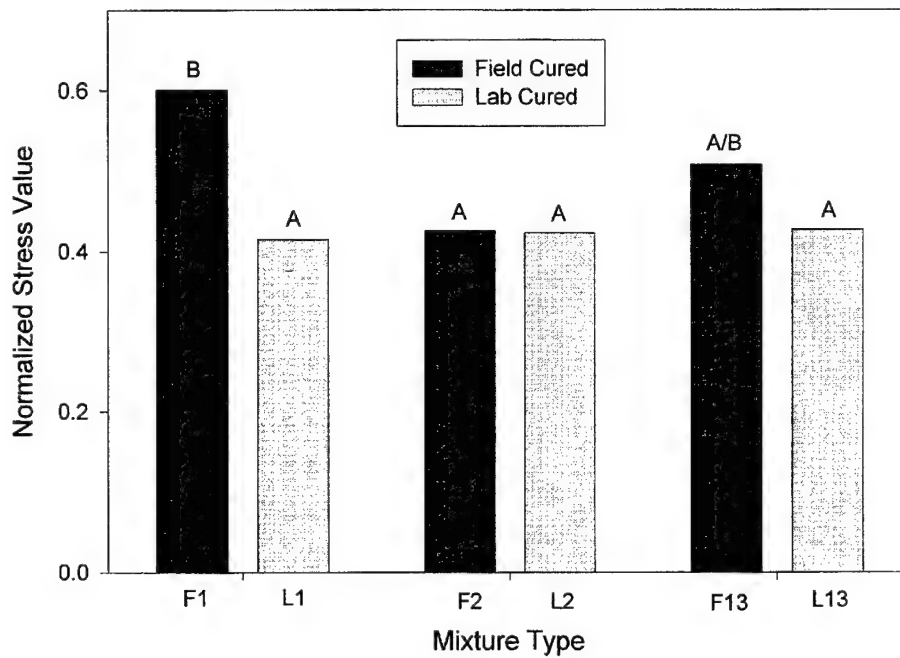
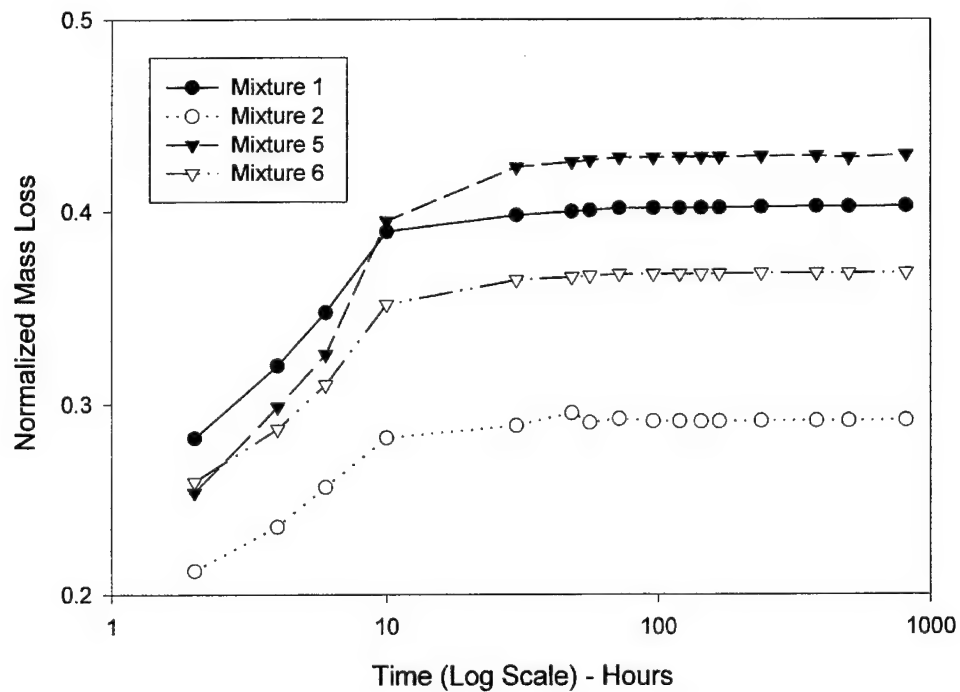
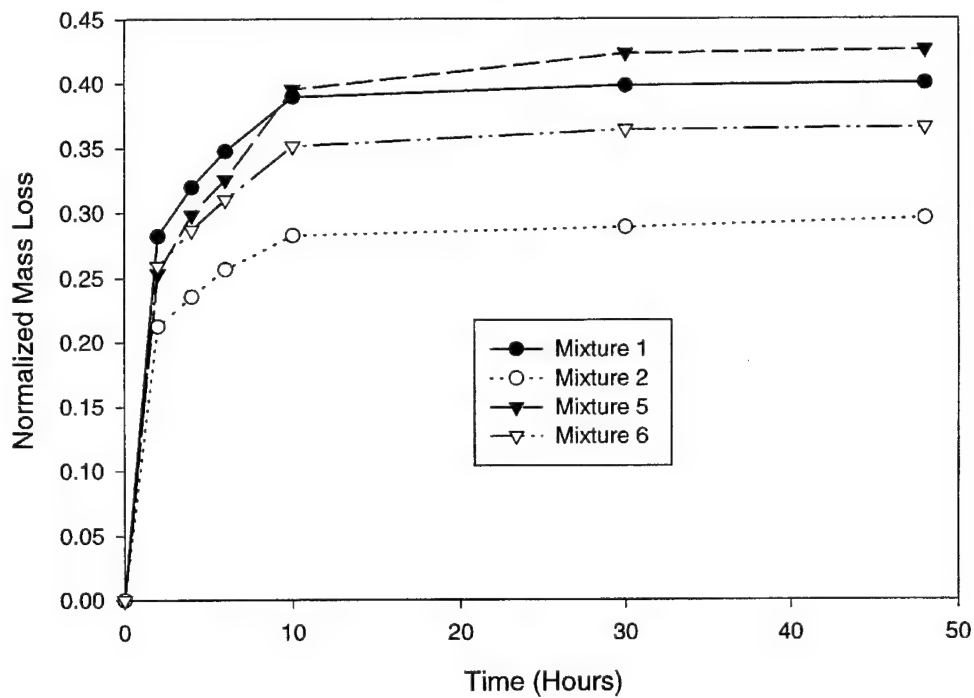


Figure 5.25 Effect of aging on normalized stress values (field (F) and laboratory (L) cured, tested at 44°C).

varying amounts of water in the different mixtures. The second and more long-term mechanism is the loss of volatile components from the coal tar. This holds true for mixtures with and without aggregate. For example, the volume of water in mixture No. 1 is approximately 42 percent; therefore, after all the water has evaporated there will be roughly a 42 percent reduction in volume of the mixture. Obtaining exact and accurate measurements of water loss of specimens from the time of fabrication is difficult because of slight variations in the moisture content of the coal-tar emulsion samples, errors in weighing relatively small amounts of ingredients, and improper mixing of the components. There is also a loss of mixture from material left in measuring and mixing containers and from material that adheres to the mold during casting and removal. Measurements taken during the fabrication of several coal-tar mixture samples showed that, within a few days of casting, the mass of the samples would vary within ± 5 percent of that anticipated from the mixture components. To illustrate the time required for complete moisture loss, various coal-tar sealer mixtures were cast at a thickness of about 5 mm (0.2 in.) in tarred-metal containers. Three specimens of each mixture were cast and these were weighed initially after casting and at increasing intervals over the next month. Cast were mixtures 1, 2, 5, and 6 (Table 3.5), and these contained approximately 42, 30, 50, and 48 percent water, respectively. The differences in mass were measurable to 0.01 percent or better based on the initial weight of the specimen. This accuracy was maintained throughout all the curing and aging mass measurements. Figure 5.26(a) illustrates the normalized mass loss of these mixtures over time on a log scale. The figure shows that the mixture with the highest percentage of water (mixture 5) had the greatest amount of mass loss,



(a)



(b)

Figure 5.26 Mass loss of Mixtures 1, 2, 5, and 6 during laboratory curing (a) Normalized mass loss versus time (log scale), (b) Normalized mass loss after a curing time of 48 hours.

while the mixture with the lowest percentage of water (mixture 2) had the smallest mass loss. Figure 5.26(b) shows that the majority of moisture loss occurs within the first 10 hours and after about 30 hours the mass becomes almost constant. The normalized mass loss for Figures 5.26(a) and (b), and other figures in this report was determined as shown below:

$$\text{Normalized Mass Loss} = (M_i - M_f) / M_i$$

where

M_i = Initial mass of specimen

M_f = Mass of specimen at given time

To illustrate effect of long-term volatile loss of various coal-tar sealer mixtures, samples of mixtures 1 through 6 were monitored for mass loss under laboratory conditions for more than two years. Each data point is the average of five separate BBR specimens and all were cured under normal laboratory conditions. The mass loss measurements could not begin until individual specimens were cut from a larger sample; therefore, the curing times given were normalized to begin the cure time approximately 14 days after the samples were cast. Figure 5.27 shows that under laboratory curing conditions, coal-tar mixture specimens will continue to age or lose mass for more than two years after fabrication. Considering the different starting point for mixtures 1 and 2, the mixtures containing more coal-tar emulsion (odd numbered mixtures) had the greater amount of mass loss throughout the test period, Figure 5.27.

A set of five BBR specimens was cut from large field-cured samples of six different mixtures from manufacturer No. 1. Figure 5.28 shows that except for one of

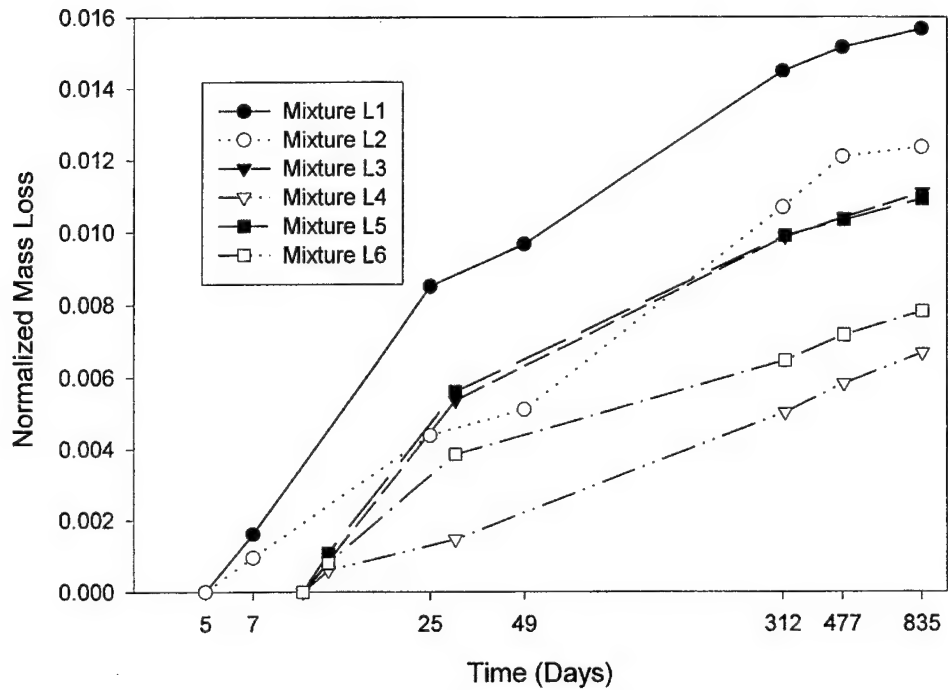


Figure 5.27 Normalized mass loss of laboratory cured mixtures 1 through 6.

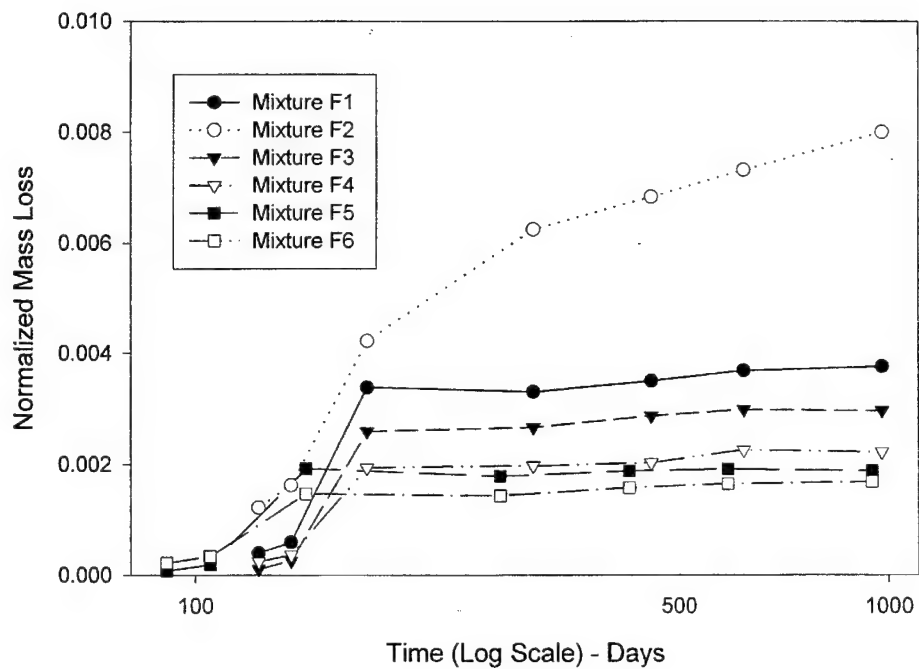


Figure 5.28 Normalized mass loss of field and laboratory cured, field mixtures 1 through 6.

the mixtures (F2), the mixtures containing more coal-tar emulsion (odd numbered mixtures) had the greater amount of mass loss throughout the test period. As discussed in chapter 2, exposed coal tar surfaces tend to have reduced loss of materials with time. Cutting or exposing a new face to fabricate the BBR specimens would expose new edges on the specimens allowing additional weight loss. Figure 5.28 shows an apparent jump in the loss of mass during a period in which the BBR test was run on the samples. These tests were run at 0°C (32°F) and it is not known if it caused the weight loss. The weight loss was relatively small and the additional handling of the specimens may have added to the amount of material or mass lost. There was no noticeable change in the amount or rate of loss of the laboratory cured specimens in Figure 5.27 when they were evaluated in the BBR device. Figure 5.29 shows several mixtures that after an initial laboratory cure of several weeks were cured for over 200 days in the field and then further cured in the laboratory. The relative difference in the amount of the percent mass loss between these mixtures is not directly comparable because of variances in timing of obtaining the original weights. These mixtures continued to show a general decrease in mass with time under laboratory conditions, even after a substantial amount of field curing. As with the other mixtures and conditions tested, the mixtures containing more coal-tar emulsion (odd numbered mixtures) had the greater amount of mass loss throughout the test period.

Effect of aggregate. The effect of aggregate on the curing of mixtures as presented in Figures 5.27 through 5.29, shows that mixtures with lower amounts of aggregate and therefore proportionally greater amounts of coal-tar sealer, generally

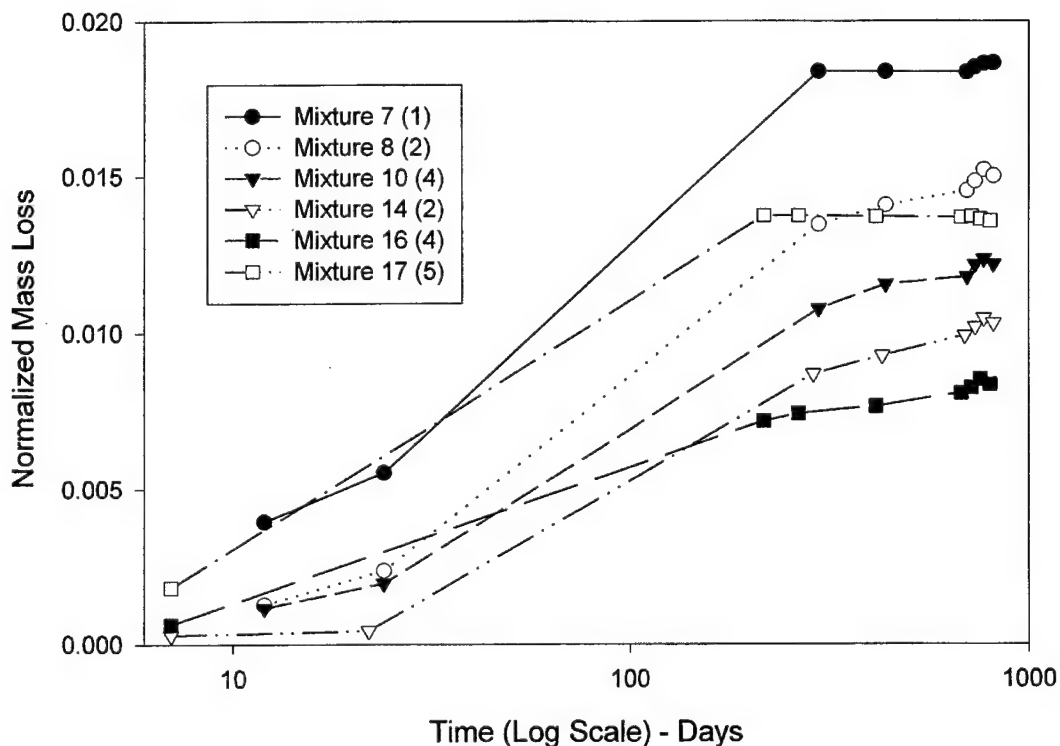


Figure 5.29 Normalized mass loss of various mixtures, field and laboratory cured. Number in brackets shows corresponding mixtures using other manufacturers' materials. Initial lab curing for about 28 days, field curing varied from about 200 to 270 days, and then additional lab curing.

exhibit a greater overall volume of mass loss. This basic trend was expected because the low aggregate mixtures have increased amounts of coal tar, which is where a long-term mass loss should occur. The only mixture that does not follow this trend is mixture 2. This may be due to the relatively high void content in the mixture, preventing or at least inhibiting the decrease in mass loss that coal-tar sealers normally develop over time.

Effect of polymer. Figures 5.27 through 5.29 show that generally, the mixtures containing polymer appear to have less long-term mass loss or at least lose it at a lower rate than mixtures without polymer. Figure 5.30, shows the effect of adding

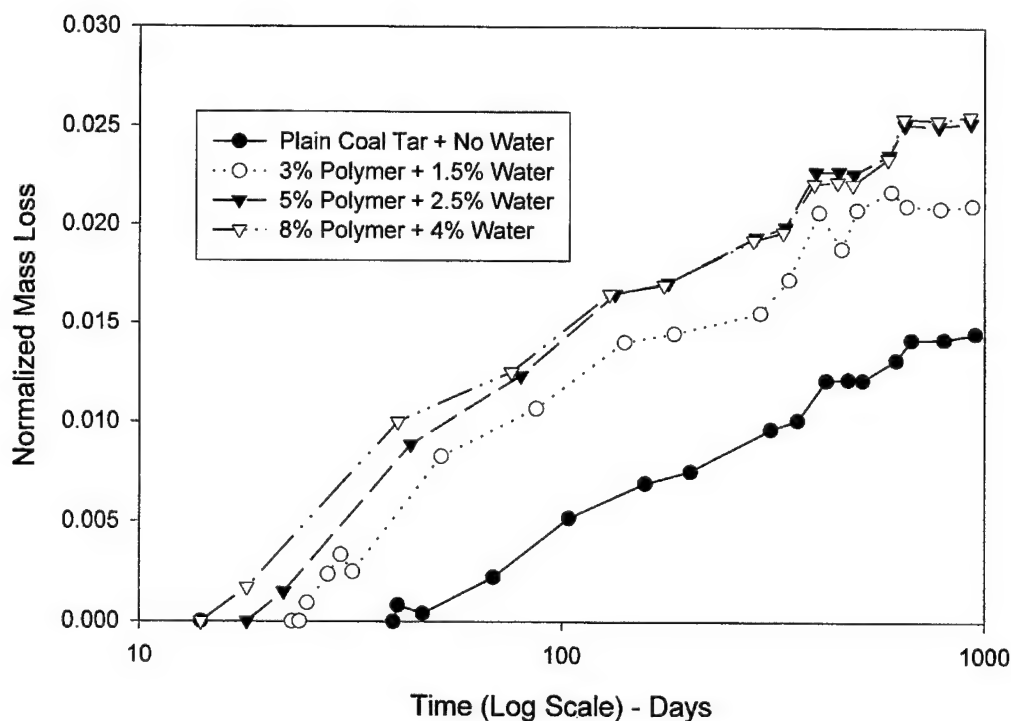


Figure 5.30 Effect of polymer content on normalized mass loss.

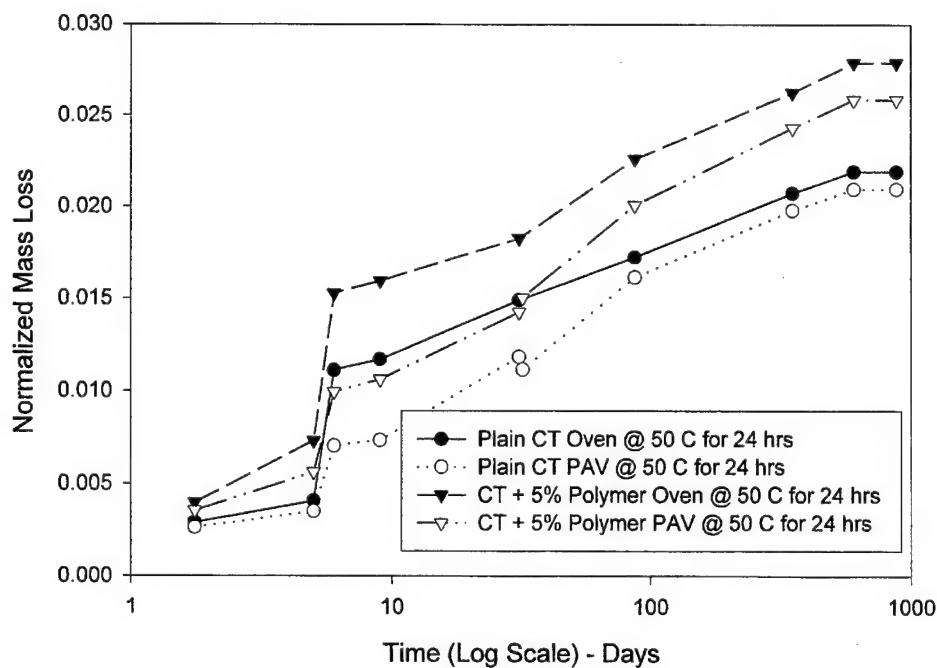
increasing amounts of polymer to a coal-tar emulsion without aggregate. In Figure 5.30 there is some offset in the amount of mass loss, mainly due to the increased amounts of water added to the polymer mixtures and contained within the polymer emulsion itself and slight differences in the age after casting. The weight loss data was normalized to account for variations in the mass of the different mixture samples. Figure 5.30 shows that change in the amount of polymer did not affect the rate of long-term mass loss and after more than two years the test specimens are approaching an asymptotic mass loss value.

Aging

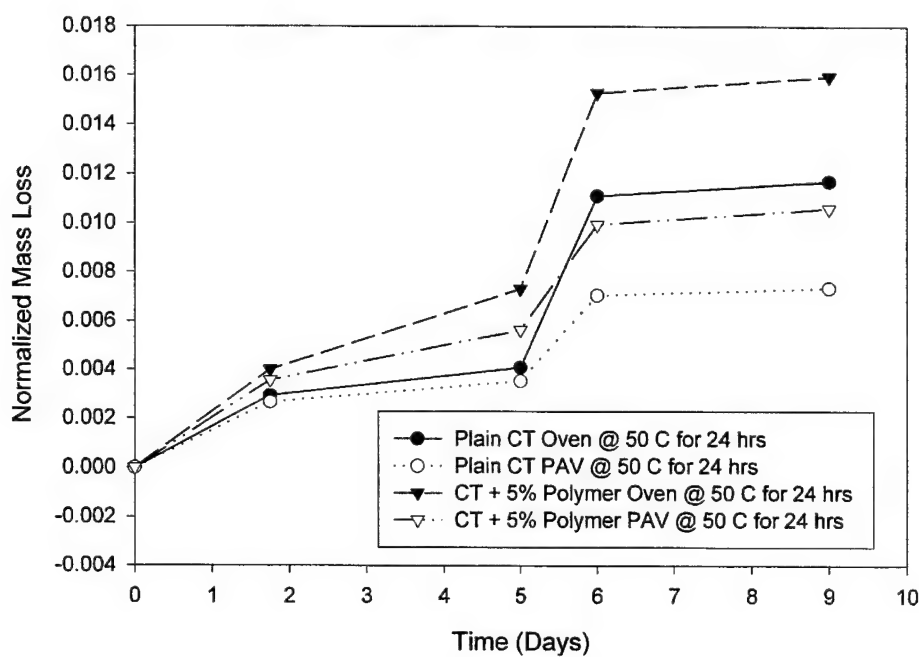
The previous section discussed how coal-tar mixtures cure and the long-term curing process can also be considered as the aging of the mixture. Recent work by

SHRP researchers on aging asphalt cement developed the pressure aging vessel (PAV) to change an asphalt cements properties consistent with several years of field exposure. Initially, plain coal-tar specimens (without aggregate) were used to investigate various methods for aging coal-tar mixtures. This was done because it is the coal tar that will age and not the aggregate in a sealer mixture. Coal tars age mainly through evaporation and, unlike asphalt cement, are relatively unaffected by oxygen; therefore, the PAV was not expected to be effective in aging coal-tar materials. The effect of curing both a plain coal tar mixture and one with a polymer additive for 24 hours in the PAV versus a forced-draft oven at 50°C (122°F) was conducted on 5 BBR sized specimens of each mixture. Figures 5.31 (a) and (b) show the mass loss that occurred during the specimens placement in either the PAV or the oven between the fifth and sixth days and that overall the oven aged specimens had a greater mass loss. As expected, the PAV acts to restrict evaporation and thereby the aging process in the coal-tar specimens. Figure 5.31 (a) shows that with additional laboratory curing the difference in mass loss after the PAV and oven procedures decreases, although the mass loss appears to be approaching an asymptotic value without becoming equal.

To develop a laboratory aging method able to age mixtures to a condition equal long-term field curing, the effects of various temperatures and aging times in conventional forced draft ovens were investigated. Figures 5.32 (a) and (b) show the effects of oven aging of plain coal-tar specimens at different temperatures. At least five specimens were weighed and the results averaged for each curing procedure investigated. These specimens were aged in a forced-draft oven at either 23°C (73°F),

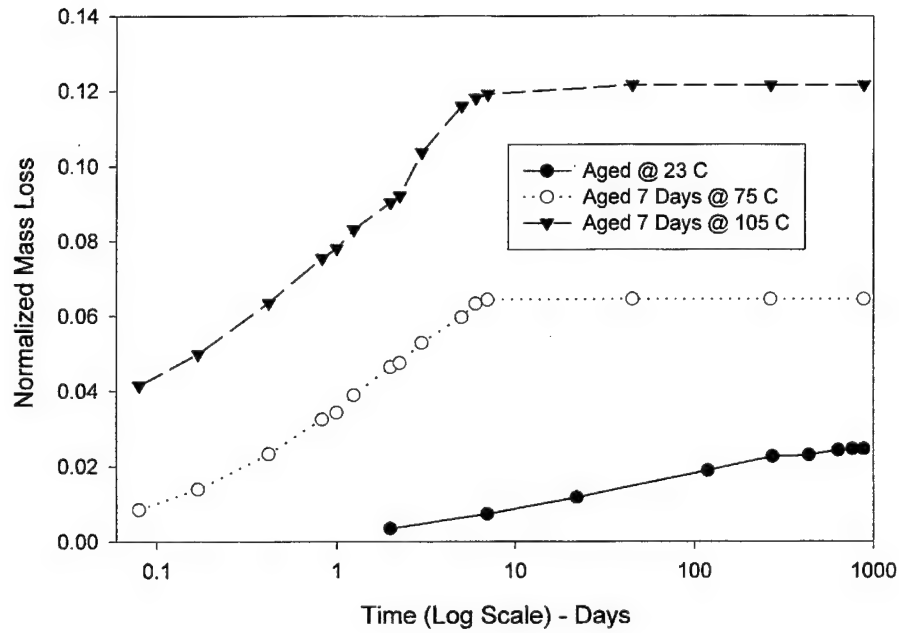


(a)

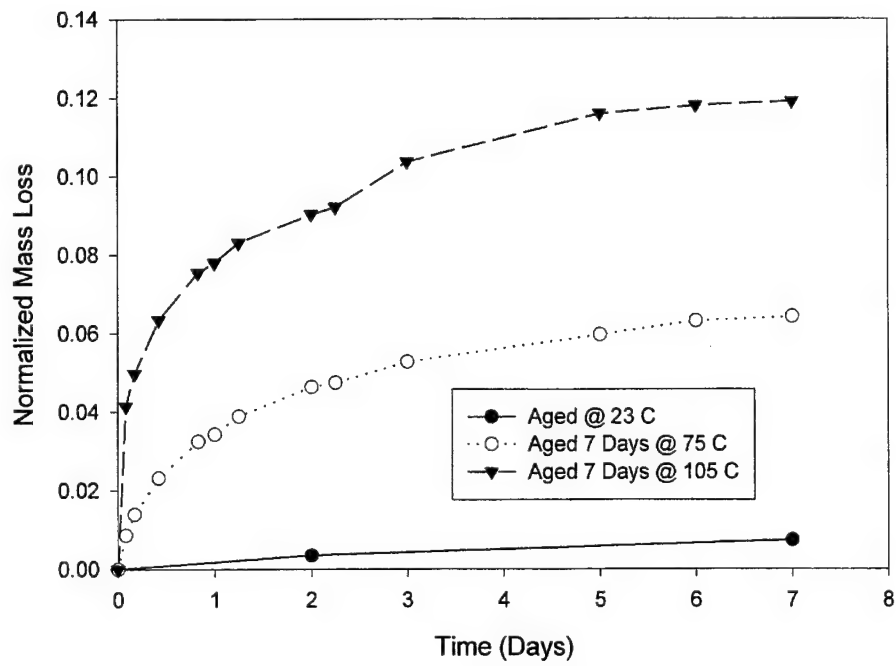


(b)

Figure 5.31 Normalized mass loss of plain and polymer modified coal tar, aged in conventional oven and PAV (a) normalized mass loss versus time (log scale), (b) Oven and PAV aging between day 5 and 6.



(a)



(b)

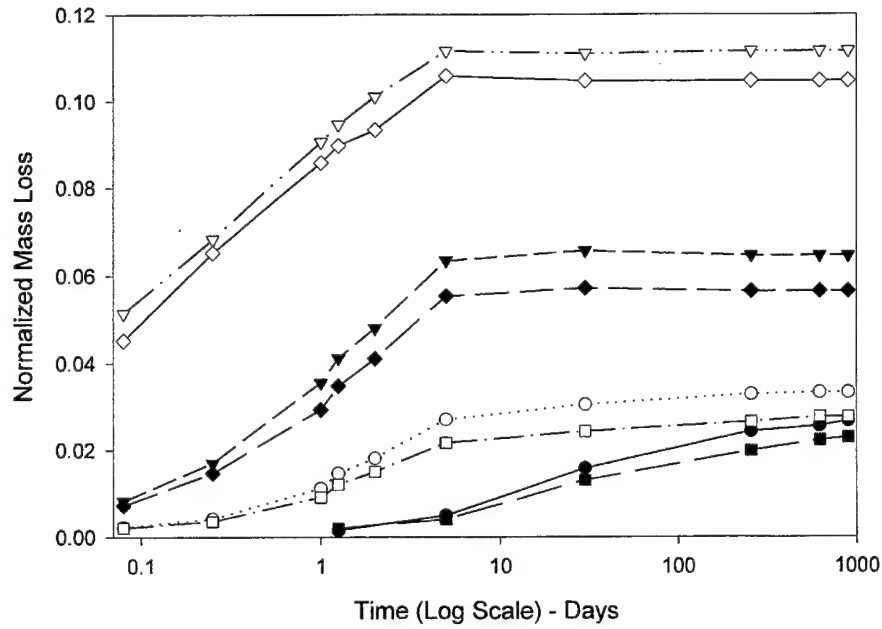
Figure 5.32. Oven curing of plain coal-tar emulsion specimens at various temperatures, (a) Normalized mass loss of specimens versus time (log scale), (b) Normalized mass loss during the first 7 days.

75°C (167°F), and 105°C (221°F). Figure 5.32 (a) shows that at 75°C (167°F) and above there was essentially no additional loss of mass at room temperature, after the specimens were removed from the oven. Figure 5.32 (b) shows that after 4° or 5° days in the oven, there was only a relatively small additional mass loss in the specimens. Upon removal from the oven, the specimens cured at either temperature did not have additional mass loss, Figure 5.32(a).

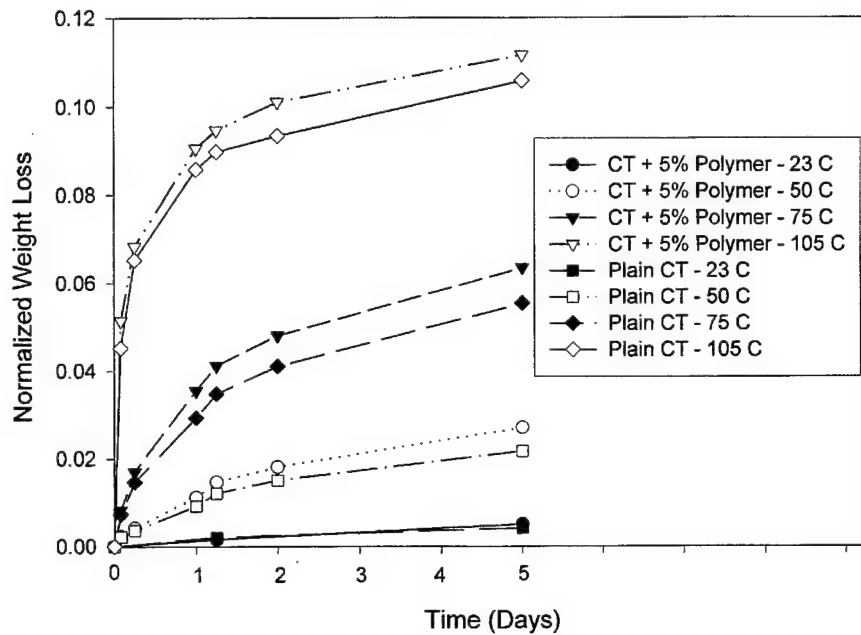
The effect of forced-draft oven aging on a polymer was investigated. Four sets of plain specimens and four sets of polymer modified specimens, each set containing five specimens was used in this evaluation. The temperatures investigated included 23°C (73°F), 50°C (122°F), 75°C (167°F), and 105°C (221°F) and the specimens were placed in the oven for 5 days. Figure 5.33(a) shows that there was a substantial difference in the loss of mass between the specimens cured at 23°C (73°F) and those oven-aged at all temperatures except those at 50°C (122°F). The specimens at the two higher temperatures had much greater losses of mass and there were no discernable losses after removal from the oven. Figure 5.33(b) shows the mass loss that occurred during oven aging and that the amount of mass loss increased with increasing oven temperatures. The specimens aged in the oven at 50°C (122°F) appear to have reached a level of constant mass after about two years. Specimens aged without the oven at 23°C (73°F) continued to lose mass; however, the rate of the mass loss appears to be decreasing with time, Figure 5.33(a).

Forced-Draft Oven Aging

The initial oven testing showed that at 75°C (122°F), specimens would obtain a nearly stable mass within a reasonable amount of time, Figures 5.32(a) and 5.33(a).



(a)



(b)

Figure 5.33 Effect of 5-day oven aging on plain and polymer modified coal-tar emulsion specimens
(a) Normalized mass loss of specimens versus days (log scale), (b) Normalized mass loss during 5-day aging.

This temperature was selected as a reasonable oven temperature for accelerated aging of coal-tar specimens. Specimens of mixtures 1 through 6 were placed in a forced-draft oven at 75°C (122°F) and then tested in uniaxial tension, Table 5.11. The data

Table 5.11 Results of Tensile Tests on Oven Aged ¹ and Corresponding Field Aged Coal-Tar Mixtures			
Mixture	Aging Time at 75°C ² (hr)	Maximum Stress (kPa)	
		Mean	COV ³
L1/F1	96	2510.0/2134.7	5.18/15.39
L2/F2	72	1936.7/2399.0	8.89/2.32
L3/F3	96	2216.7/1627.3	5.68/6.73
L4/F4	72	2045.0/1690.0	4.50/4.28
L5/F5	72	2188.3/2230.0	2.17/3.56
L6 ⁴ /F6	72	---/2795.0	---/2.18
¹ Specimens aged in a forced-draft oven at 75°C. ² Time of aging until there was no further statistical change in mean of laboratory (L) specimens ³ Coefficient of variation (COV) = (Std. Deviation/mean) × 100. ⁴ Only one L6 specimen tested for each cure time. Values at 48, 72, and 96 hours of aging equaled 2050, 2220, and 2210, respectively.			

for the laboratory aged samples (non-aged) was obtained from previously run tension tests. Three specimens of each mixture were aged in the oven for up to 24, 48, 72, 96, and 120 hours and then run in the tension test. Due to sample fabrication problems only one specimen was available for each aging time for mixture L6. Using a 95 percent confidence level, the results of the individual tests at each level of aging were found to be not significantly different. A one-way analysis of variance (ANOVA) was performed, using SPSS version 9.0 software, to determine the level of aging at which there was no significant difference (increase) in stress values. This was accomplished by running the ANOVA with the stress levels from each aging regimen. Eliminating the results of non-aged specimens and running the ANOVA on the

remaining results then continued the process. The next lowest set of results was then eliminated (the 24-hour results) and process continued in this manner until the output showed that there was no difference between the values. This procedure was used to determine the time of aging required at the selected conditions to reach the maximum stress level that could be achieved for each mixture.

Table 5.11 also includes tensile stress values from corresponding field aged specimens. The results show that aging specimens at the given oven conditions for the time listed can provide tensile properties similar to those achieved by long term field aging of specimens. The aging time required to achieve a level of stress in the tensile test to where no further significant changes in material properties occurred varied from 72 to 96 hours. The results generally indicate that 6 to 8 months of field exposure in Vicksburg, MS would age the specimens to at or near the point where further aging would not affect their tensile properties.

THERMAL PROPERTIES

Coal-Tar Emulsion Mixtures

The coefficients of thermal expansion of sealer mixtures 1 through 6 was measured over a temperature range of 2°C (6°F) to 44°C (111°F), Table 5.12. The coefficient of thermal expansion (C) can be calculated from the following formula:

$$C = \Delta L / (G \Delta T)$$

where

C = coefficient of thermal expansion ($10^{-5}/^{\circ}\text{C}$)

ΔL = change in length between temperature changes (mm)

G = gage length of test specimen

ΔT = change in temperature during evaluation

Table 5.12 Coefficient of Thermal Expansion Test Results on Sealers				
Curing Method	Mixture Number	Thermal Coefficient ($\times 10^{-5}/^{\circ}\text{C}$)		
		Mean	Standard Deviation	CV (%) ¹
Field Cured	1	6.64	0.199	3.0
	2	3.00	0.410	13.6
	3	6.39 ²	--	--
	4	5.31	0.147	2.8
	5	6.05 ³	--	--
	6	5.42	0.116	2.1
Laboratory Cured ⁴	2	2.73	--	--
	4	5.22	--	--
¹ Coefficient of Variation (%) = Standard Deviation/Mean $\times 100$. ² Mean of two values (6.62 and 6.15). ³ Mean of two values (6.22 and 5.87). ⁴ One test for each mixture tested.				

The values obtained were relatively constant for all the mixtures except for the non-polymer-modified mixture with higher amounts of aggregate (mixture 2), which was about one half the value of the others. Mixtures containing greater amounts of aggregate showed a slightly lower coefficient of thermal expansion when compared to similar mixtures containing less aggregate. This compares well to the field test section results where the mixtures with greater amounts of aggregate performed better.

Underlying Hot-Mix Asphalt Pavement

The coefficient of thermal expansion of the underlying hot-mix pavement was evaluated between temperatures of -22°C (-7.6°F) and 10°C (50°F), Table 5.13. Measurements were taken approximately every 1/2-hour from 2 to 6 hours after the start of the test until consistent results were obtained. It took longer for the specimens to reach a stable length at the lower test temperature. The average thermal coefficient determined for this hot-mix asphalt as $2.12 \times 10^{-5}/^{\circ}\text{C}$. This result falls well within the

Table 5.13 Coefficient of Thermal Expansion Test Results of Hot-Mix Asphalt				
Sample Number	Gage Length, mm (G)	Overall Temperature Change, C (ΔT)	Change in Length, mm (ΔL)	Thermal Coefficient, $10^{-5}/^{\circ}\text{C}$ (C)
1	282.00	32	0.1880	2.0829
2	282.82	32	0.1905	2.1049
3	281.43	32	0.1956	2.1717
4	282.43	32	0.1930	2.1359
Average				2.1239

general range of 1.7 to $3.0 \times 10^{-5}/^{\circ}\text{C}$ of values reported by other researchers (Kanerva, et al. 1994 and Janoo, et al. 1995).

SUMMARY

The results of the fuel resistance tests showed that the amount of polymer in the coal-tar mixture had a noticeable effect on its fuel resistance. An increase in the amount of polymer in the mixture resulted in an increase in the amount of aggregate that could be incorporated into the mixture and still maintain fuel resistance,

Table 5.2.

Obtaining relatively accurate viscosity values of coal-tar emulsions or coal-tar mixtures requires specialized equipment not normally found in standard testing laboratories. The use of the initial readings obtained with a Brookfield viscometer can provide reasonable values of viscosity, Table 5.3. However, the relatively wide range in viscosity at which coal-tar mixtures are acceptable for handling and placement reduces the suitability of using viscosity as a mixture design parameter.

Freeze-thaw test methods can provide a useful indication of coal-tar mixture field performance, Tables 5.4 and 5.5. A proposed freeze-thaw method (Sebaaly et al. 1999) was adapted to shorten the testing period and to make it easier to use.

The results of the BBR testing on both plain coal tar and coal-tar mixtures showed an increase in creep stiffness with age. Testing of plain coal tar showed that this increase approached an asymptotic value and that there was little effect from varying the amount of polymer, Table 5.6. BBR testing of various coal-tar mixtures also showed that the mixtures with higher amounts of aggregate had greater creep stiffness, Table 5.7. The BBR results for the mixtures, particularly the field-aged specimens, had relatively high COV's, Table 5.7. A statistical analysis showed that in most instances the BBR results were not able to produce discernable differences between the sources of the coal-tar emulsions, Figure 5.3.

DSR evaluation of coal-tar emulsions was not possible because of the cured properties of the emulsions. DSR testing was performed on the base tars that were used to manufacture two of the emulsions. The results showed that the properties of the coal tar varied greatly with small changes in temperature, when compared to asphalt cement. The coal tar used to make the emulsion for Mixtures 1 through 6 had a larger phase angle and lower complex modulus, when compared to that used for Mixtures 13 through 18, Table 5.8. The coal tar used to make Mixtures 1 through 6 was not as stiff and this emulsion did perform better in the field.

Uniaxial tension results showed that the source of the coal-tar emulsion could have an effect on the tensile stress at failure for specimens with minimal curing, Figures 5.5 and 5.6. Higher amounts of aggregate in the sealer mixtures generally resulted in higher tensile stress values, although, the amounts were not normally statistically significant, Figures 5.7 and 5.8. Increases in the test temperature resulted in lower tensile stresses; these were statistically significant in most instances,

Figure 5.9. At 23°C (77°F) the lower amount of polymer produced substantially lower tensile stress values than the higher amount or no polymer mixtures,

Figure 5.10. At 44°C (111°F) the addition of polymer caused a significant reduction in tensile stress for the mixtures containing lower amounts of aggregate, Figure 5.11. While the mixtures with higher amounts of aggregate had no significant difference, aging of the coal-tar mixtures resulted in significantly higher tensile stress levels at both test temperatures, Figures 5.12 and 5.13.

The normalized stress levels in most instances decreased rapidly to about 40 to 60 percent of the initial stress value. The source of the coal-tar emulsion didn't have a significant effect on the normalized stress values obtained, regardless of the temperature or age of the test specimens, Figures 5.15 through 5.16. The amount of aggregate was only significant in field cured or aged specimens. At 23°C (73°F) the mixture with a higher amount of aggregate had an increased normalized stress value, while at 44°C (111°F) the low aggregate mixture had an increased stress value, Figures 5.17 and 5.28. A temperature change of 23°C (73°F) to 44°C (111°F) did not affect normalized stress values, except for the field-cured mixture with a high amount of aggregate (F2), Figure 5.19. At 23°C (73°F), the addition of polymer lowered the normalized stress values for all field- and laboratory-cured mixtures and the decrease was significant in all instances but one (mixture F5), Figures 5.20 and 5.22. At 44°C (111°F), only one field- and laboratory-cured mixture (F6) was significantly different from the mixture without polymer, Figures 5.21 and 5.23. Aged specimens had higher normalized stress values, although they were not significantly greater in all cases, Figures 5.24 and 5.25.

The water that is contained within coal-tar emulsion mixtures generally evaporates within 30 hours, Figures 5.26(a) and 5.26(b). Coal tar materials loose mass and harden over time through evaporation of volatile compounds and this mass loss slows to almost nothing after a few months or years depending upon curing conditions, Figures 5.27 through 5.29. Mixtures with relatively lower amounts of aggregate, because they have proportionately higher amounts of coal tar, generally lost more weight from evaporation. The addition of polymer in the mixtures resulted in a reduced mass loss when compared to mixtures without polymer, Figures 5.27 through 5.29. The results obtained in curing specimens of various amounts of polymer without aggregate showed that amount of polymer did not greatly affect the rate of mass loss, Figure 5.30.

Investigation of an aging procedure found that, as expected, the PAV method for aging asphalt cement was not as effective as curing in a forced-draft oven, Figures 5.31(a) and (b). Coal-tar mixtures, with and without polymer, were aged for 5 days in a forced-draft oven at 75°C (167°F) did not lose additional mass under laboratory conditions, Figures 5.33(a) and (b).

Tensile testing of various coal-tar mixture specimens, aged in a forced-draft oven at 75°C (167°F), showed that there was no significant change in values after 3 to 4 days of aging, Table 5.11. The tensile stress values obtained at these times was equivalent to that obtained from tensile tests on specimens field cured for about 6 to 8 months. Generally, mixtures containing more coal tar required longer aging times to reach a consistent tensile strength value.

Test procedures were developed for this study to determine the coefficient of thermal expansion for the various coal-tar emulsion mixtures and for the underlying hot-mix asphalt. The coefficient of thermal expansion of the cured coal-tar emulsion mixtures was about 1.5 to 3 times greater than the underlying hot-mix asphalt.

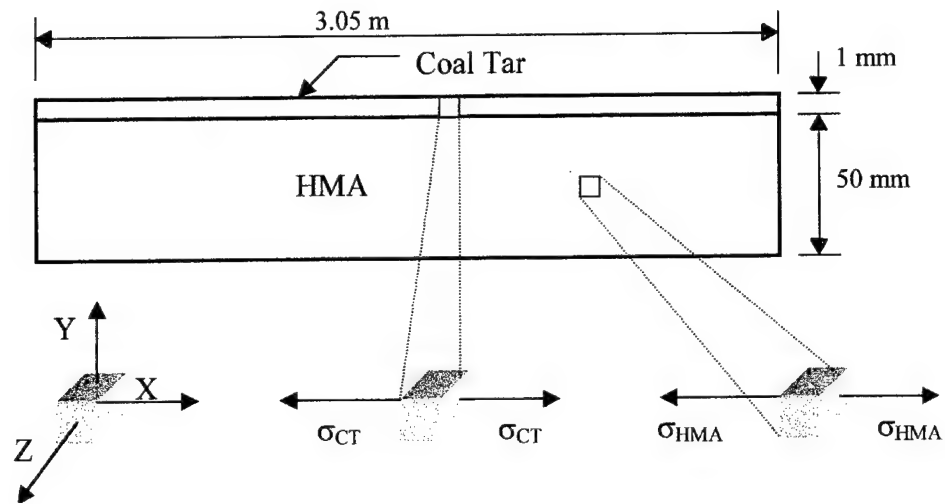
CHAPTER 6: CRACKING MECHANISMS

INTRODUCTION

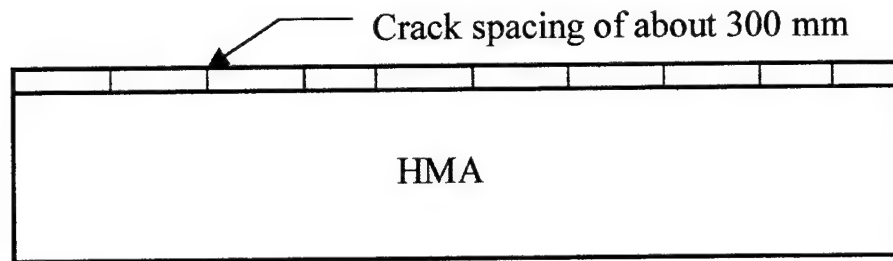
The useful life of coal tar sealers, before excessive cracking requires reapplication, has ranged between 2 to 5 years (Hoiberg 1966b and Saraf, Majidzadeh, and Kumar 1992). The type of cracking that normally develops is similar to the crazing cracking in portland cement concrete (PCC) pavement or the cracks that occur in the surface of a cohesive soil when it is dried excessively, as shown in Figure 3.17. This type of cracking occurs in the sealer in both trafficked and non-trafficked areas. A coal tar sealer is a relatively thin layer (1 to 2 mm (0.04 to 0.08 in.)) of mixture placed on top of a hot-mix asphalt surface, Figure 6.1 (a). The coal tar sealer and the underlying hot-mix asphalt surface are constantly undergoing movement caused by thermal stresses. The rate of this movement is depended on the temperature gradient within the pavement and the thermal properties of the individual material types that make up the pavement. Coal-tar sealer mixtures, at least within the first few years of service, have been shown to be losing mass (Figures 5.29 and 5.31) and increasing in stiffness as measured by the BBR and uniaxial tension tests. The thermal and shrinkage factors acting either separately or together are responsible for cracking in coal-tar sealers.

DEFORMATION OF COAL-TAR SEALERS

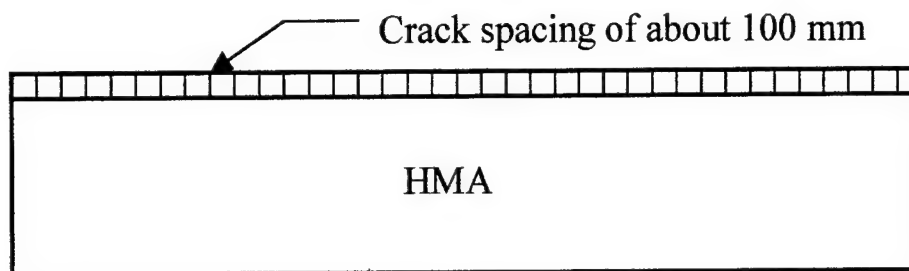
The rate of loading or movement of the sealer caused by the thermal changes in a pavement structure is relatively slow compared to traffic type loading. Figure 3.22 shows the typical temperature variations that occurred on the pavement surface of the coal-tar sealer test section and the surrounding pavement. The greatest



(a)



(b)



(c)

Figure 6.1 Schematic representation of sealed pavement section
 (a) Stress direction and values in plane strain condition for coal-tar sealer and underlying HMA caused by temperature variations, (b) and (c) Variations in crack width.

changes in temperature occur at the surface and decrease with increasing depth within the pavement. The temperatures generally cycle in similar patterns from day to day depending upon climatic conditions. There is usually an increase in temperature in the morning, especially if the sun is out, Figure 3.23. The temperature rises and then approaches an asymptote value, especially on a warm, sunny day. At the end of the day the temperature starts to decrease as the sun sets and then continues throughout the night until the sun rises the next morning. The extremes in these cycles are controlled by climatic events such as the amount and duration of cloud cover, rainfall, and the specific season of the year. The relative differences in thermal movement between the sealer and the underlying HMA caused by the different temperature variations and different material properties, causes a buildup of stress between the two materials. Because of the relatively slow rates and variation in the amount of movement, the coal-tar sealer is strained slowly allowing stress relaxation to occur. The curing shrinkage and hardening that occurs in the sealer, with age, is another factor that adds to the stress on the sealer. Because the hardening occurs mainly through evaporation, the coal-tar sealer will shrink from the top down adding to the stress over time. The bond between the coal-tar sealer and the underlying HMA is normally very good. The effect of the differential movement, shrinkage, and a good bonding is the formation of cracks in the surface of the sealer.

The field test sections that cracked completely throughout could be grouped into two basic crack spacing layouts, those with wide spacing (Figure 6.1 (b)) and those with narrower spacing (Figure 6.1 (c)). At the time of the first cracks appearing in the sealer test sections, the maximum temperature difference occurring within one

day (actually during an 8-hour time span from early morning to early afternoon) was 34°C (61°F) (6°C (11°F)), within one hour), Figure 3.23. An estimate of the amount of movement, ΔL , that could be expected within an hour due to this temperature change, can be obtained by rearranging Equation (5.1) to obtain Equation (6.1).

$$\Delta L = C (G \Delta T) \quad (6.1)$$

where

ΔL = change in length between temperature changes (mm)

C = coefficient of thermal expansion ($10^{-5}/^{\circ}\text{C}$)

G = gage length of test specimen

ΔT = change in temperature during evaluation

The amount of movement that will occur within the sealer and the underlying HMA will depend upon their respective coefficients of thermal expansion. For field-cured sealer mixtures the coefficients ranged from 3.00 to $6.39 \times 10^{-5}/^{\circ}\text{C}$, Tables 5.12 and 6.1. The overall range of movement for the length of the sections, as shown in Figure 6.1 (a) and (b), for a 6°C (11°F) temperature change would theoretically vary from 0.54 to 1.195 mm for the coal tar mixtures. The amount of movement in the HMA for the above conditions would be 0.382 mm, Tables 5.13 and 6.1. The amount of movement for the sealer mixtures and the underlying HMA, considering the two crack widths illustrated in Figure 6.1 (a) and (b), is given in Table 6.1.

Shrinkage or the reduction in volume of the sealer mixtures could cause movement in the sealer. As shown in Figures 5.28 through 5.31, the majority of mass loss, depending upon curing conditions, occurs generally within a few hours and losses are relatively slow thereafter. These results agree with previous research that

Table 6.1 Pavement Movement Due to Thermal Changes in One Hour			
Mixture Number ¹	Coefficient of Thermal Expansion ($10^{-5}/^{\circ}\text{C}$)	Amount of Movement for Given Crack Width	
		300 mm	100 mm
F1	6.64	0.1195	0.0398
F2	3.00	0.0540	0.0180
F3	6.39	0.1150	0.0383
F4	5.31	0.0956	0.0319
F5	6.05	0.1089	0.0363
F6	5.42	0.0976	0.0325
L2	2.73	0.0491	0.0164
L4	5.22	0.0940	0.0313
HMA	2.124	0.0382	0.0127
1 – F = field cured, L = lab cured, HMA = underlying hot-mix asphalt			

showed that the loss of material through evaporation decreases as the exposed surface of the coal tar skins over and further loss of volatiles is minimized (Hoiberg 1966a). The initial, high volume losses are from water loss from the emulsion and the added water and the slower, long-range losses, are through volatile (non-water) losses. After the initial volume losses, the short-term shrinkage movements (within several hours or a few days) that would occur in a mixture that had been in place for several months would be negligible.

The values of pavement movement given in Table 6.1 for the sealers and the HMA caused by thermal changes are based on unrestrained movement. The HMA, because of a lower coefficient of thermal expansion, does not move as much as the sealer. Therefore, the HMA will act to restrain the sealer's movement with changes in temperature. Because of the relatively thin layer thickness of the sealer the temperature at the surface of the underlying HMA should be about the same or only marginally lower than that of the sealer.

TENSILE PROPERTIES

As shown in Figure 6.1 (a), the relatively small volume of the pavement structure in the y direction in relation to the x and z directions allows the action of thermal movement to be considered in only two dimensions. By considering this to be a plane stress case, acting uniaxially across a one-unit width of material in the z direction, the movement in the x direction can then be considered as a plain strain problem. This plain strain or uniaxial state of stress occurs when there is stress in only one plane. In other words, the stresses in the other planes, σ_y and σ_z , are equal to zero.

The effects of time and temperature on the tensile properties of both HMA and coal-tar sealers are summarized in Tables 6.2 and 6.3. The indirect tension test results reported in Table 6.2 were obtained from two separate studies (Lynch, et al. 1997 and Ahlrich 1997). Table 6.2 shows the effect of aging or the use of a harder asphalt binder on HMA airfield pavements. This effect causes a brittle failure, with the HMA having a higher tensile strength with a correspondingly lower deformation. Table 6.3

Table 6.2

Effect of Grade and Age of the Binder on the Tensile Strength of Airfield HMA Pavement Mixtures

Binder	Temperature, °C (°F)	Tensile Strength, kPa (psi)	Deformation ¹ at Ultimate Load, mm (in.)
AC-20 ²	25 (77)	1,390 (202)	0.9 (0.035)
	40 (104)	268 (39)	0.55 (0.022)
AC-20 ^{2,3}	25 (77)	2,710 (395)	0.5 (0.020)
	40 (104)	1,500 (218)	0.45 (0.018)
AC-20 ⁴	25 (77)	687 (99.6)	---
	40 (104)	294 (42.7)	---
AC-40 ⁴	25 (77)	2,087 (302.7)	---
	40 (104)	492 (71.4)	---

¹ – Deformation at which load begins to decrease

² – Mixture performance properties obtained from Lynch, et al. 1997.

³ – AC-20 aged for 24 hours at 149°C (300°F).

⁴ – Mixture performance properties obtained from Ahlrich 1997.

Table 6.3 Effect of Sealer Proportions and Aging on the Tensile Strength of Coal-Tar Mixtures				
Mixture ¹	Temperature °C (°F)			
	23 (73.4)		44 (111.2)	
	Tensile Strength ² , kPa (psi)	Deformation ² , 100%/75%, mm (in.)	Tensile Strength, kPa (psi)	Deformation ³ , 100%/75%, mm (in.)
F1	1900 (276)	1.27/2.47 (0.050/0.097)	880 (128)	1.18/2.13 (0.047/0.084)
F2	2230 (323)	0.77/0.97 (0.030/0.038)	798 (116)	0.67/1.27 (0.026/0.050)
F3	1641 (238)	2.68/6.93 (0.106/0.273)	720 (104)	2.98/5.60 (0.117/0.221)
F4	1716 (249)	2.64/7.33 (0.104/0.289)	901 (131)	1.34/2.33 (0.053/0.092)
F5	2404 (349)	3.57/8.17 (0.141/0.322)	702 (102)	3.97/10.61 (0.156/0.418)
F6	2648 (384)	1.78/3.33 (0.070/0.131)	983 (143)	1.88/4.56 (0.074/0.180)
L1	360 (52)	2.28/4.17 (0.090/0.164)	136 (19.7)	2.23/4.06 (0.088/0.160)
L2	550 (80)	0.90/1.62 (0.035/0.064)	315 (46)	0.48/0.83 (0.019/0.033)
L3 ⁴	492 (71)	2.40/7.50 (0.095/0.295)	140 (20.3)	2.87/6.00 (0.113/0.236)
L4 ⁴	976 (142)	1.33/2.87 (0.052/0.113)	291 (42)	0.77/1.23 (0.030/0.048)
L5 ⁴	421 (61)	2.73/13.67 (0.108/0.538)	185 (26.8)	3.23/8.83 (0.127/0.348)
L6 ⁴	539 (78)	2.50/8.83 (0.098/0.348)	143 (20.7)	3.87/6.83 (0.152/0.269)
¹ – Designations – F: field cured for 8 to 10 months, L: laboratory cured for 3 to 4 weeks. ² – Average of 3 specimens. ³ – Deformation at which load begins to decrease (100%) and when load decreases 75%. ⁴ – Only 1 specimen tested.				

shows that the various coal-tar mixtures follow the same trend toward brittle failures as they age as did HMA mixtures with harder binders.

The loading and unloading load-deformation curves of indirect tensile tests on the airfield HMA are typically symmetrical. The aged or field cured mixtures of coal tar without polymer and especially those containing more aggregate produced nearly symmetrical curves. The term symmetrical curve signifies that the loading curves have approximately equal or similar slopes during both loading and unloading. Symmetrical curves are indicative of a brittle failure while a non-symmetrical curve would signify a more ductile failure. One method of quantifying this type of failure is to observe the length of time or amount of strain over which a mixture still has substantial tensile strength after reaching its maximum tensile strength value. This difference is illustrated by giving the deformation at the ultimate load and when the load has decreased by 25 percent, as given in Table 6.3. The net effect of aging on both the asphalt and coal tar materials is that, for a given amount of movement, there is a resulting greater tensile stress versus non-aged specimens. Table 6.3 shows that generally mixtures with polymer and lower amounts of aggregate had more ductile (non-brittle) failures. These mixtures showed increased toughness (measure of energy), which is represented by the area under the stress-strain curve. Figure 6.2 illustrates this increased ductility effect on the shape of the loading and unloading load-deformation curves for increased amounts of polymer for both field and laboratory cured specimens.

The crack spacing patterns shown in Figure 6.1 (b) and (c) are indicative of what occurred in the field test sections. As discussed in Chapter 3, cores taken through the cracks showed that they had occurred only in the sealer and had not penetrated into the underlying HMA. The cracking indicates that the tensile stresses

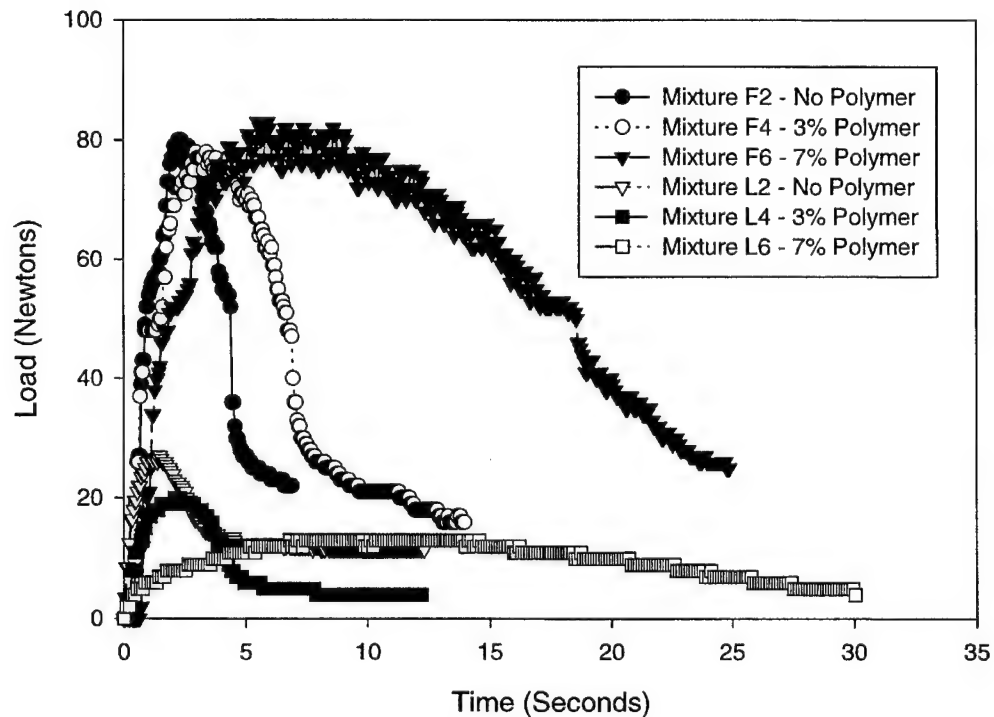


Figure 6.2 Load versus time for field (F) and laboratory (L) cured mixtures 2, 4, and 6, with higher amounts of aggregate at 44°C.

developed due to the thermal movements exceeded the tensile or cohesive strength of the sealer. In Figure 6.1 (b) a crack spacing of 300 mm (12 in.) is illustrated and for the conditions as given in Table 6.1, mixture F1 would have had a resulting movement of 0.12 mm (0.0047 in.) for a temperature change of 6°C (11°F). However, the underlying HMA layer would have moved only 0.038 mm (0.0015 in.), resulting in a residual stress within the coal tar sealer. Mixture F1 would crack when the stress developed from the 0.082 mm (0.0032 in.) of restrained movement exceeded the tensile strength of the mixture. Table 6.1 shows that as the coal tar sealer mixtures age there is a minimal overall affect on their thermal expansion properties.

To evaluate the actual stresses that develop in the sealer from the known thermal movement, a modulus value that relates the state of strain to a corresponding state of stress is required. The amount of residual strain that resulted from the 6°C (11°F) change in temperature was calculated for each mixture, as given in Table 6.4. Direct tension tests run on each material were used to obtain an elastic modulus or modulus of elasticity (E) for each mixture at the amount of strain shown. Viscoelastic materials will generally exhibit some elastic properties, at least at very small units of strain. Table 6.4 provides a listing of the modulus of elasticity values for the various mixtures and their corresponding tensile stress values. The values were obtained from tension tests run at a relatively fast strain rate when compared to the movement caused by thermal changes. Because of the difference in strain rates the modulus and corresponding tensile stress values, Table 6.4, would be expected to be greater than

Table 6.4 Modulus and Resulting Tensile Stress Values From Direct Tension Tests at Strain Levels Caused by Restrained Movement from a 6°C (11°F) Change in Temperature				
Mixture	Test Temperature, °C (°F)	Strain (μE)	Modulus of Elasticity (E), MPa (kpsi)	Resulting Tensile Stress, kPa (psi)
F1	23 (73)	271	1,568 (227)	425 (62)
	44 (111)		948 (137)	257 (37)
F2	23 (73)	53	4,811 (697)	255 (37)
	44 (111)		2,925 (424)	155 (42)
F3	23 (73)	256	1,277 (185)	327 (47)
	44 (111)		199 (29)	51 (7)
F4	23 (73)	191	1,118 (162)	214 (31)
	44 (111)		1,165 (169)	223 (32)
F5	23 (73)	236	2,061 (299)	486 (71)
	44 (111)		267 (39)	63 (9)
F6	23 (73)	198	1,955 (284)	387 (56)
	44 (111)		863 (125)	171 (25)
F13	23 (73)	271	1,860 (270)	504 (73)
	44 (111)		1,004 (146)	272 (39)
F15	23 (73)	256	1,723 (250)	441 (64)
	44 (111)		711 (103)	182 (26)

those actually experienced in the field. Table 3.9 contains the tensile strength values of corresponding field mixtures. A comparison of these tensile strength values shows the field tensile strength values were higher than the estimated tensile stress applied when cracking occurred. These thermally caused stresses are applied at a low rate and on a relatively continuous basis. Therefore, the ability of a material to relax or not build up stress over time is important and is discussed in the following section.

EFFECT OF STRESS RELAXATION

The thermal and shrinking processes involved in the movements of a coal-tar sealer on a hot-mix asphalt pavement are similar to the movements that occur during a stress relaxation test. The total strain, ϵ_T , on the system is equal to the sum of all strains and can be represented as shown in Equation (6.2).

$$\epsilon_T = \sum \epsilon = \epsilon_{\text{Thermal}} + \epsilon_{\text{Shrinkage}} \quad (6.2)$$

where

$\epsilon_{\text{Thermal}}$ = strain caused by thermal movement

$\epsilon_{\text{Shrinkage}}$ = strain caused by shrinkage of sealer

The total stress, σ_T , on the system is equal to the sum of all stresses and can be represented as shown in Equation 6.3.

$$\sigma_T = \sum \sigma = \pm \sigma_{\text{Thermal}} + \sigma_{\text{Shrinkage}} \quad (6.3)$$

where

$\epsilon_{\text{Thermal}}$ = stress caused by thermal movement

$\epsilon_{\text{Shrinkage}}$ = stress caused by shrinkage of sealer

As discussed in Chapter 2, the stress-relaxation test is an appropriate method to illustrate the viscoelastic properties of coal-tar sealer mixtures. Figure 6.3 shows the

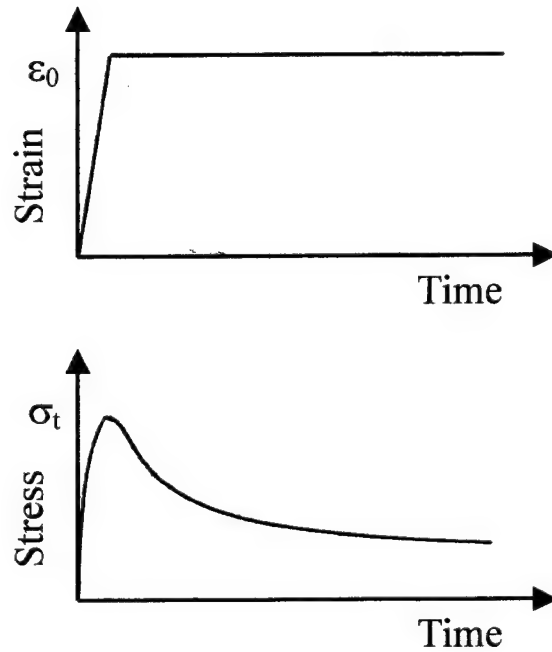


Figure 6.3 Typical stress relaxation behavior.

results of an idealized stress relaxation test of a coal-tar mixture illustrating the initial strain, time-dependent stress levels, and the resulting permanent strain. One method of evaluating the results of this test is the determination of relaxation modulus values as given by Equation 6.4.

$$E_R(t) = \sigma(t)/\epsilon(t) \quad (6.4)$$

where

$E_R(t)$ = relaxation modulus at time t

$\sigma(t)$ = stress value at time t

$\epsilon(t)$ = constant strain value

As shown in Figure 6.3, during the near instantaneous strain, the stress value rises to its highest level and then decreases as the material relaxes.

The results presented in Chapter 5 of a stress relaxation evaluation showed that the rate of strain used in the evaluation produced results within the limits of linear viscoelasticity. These results also illustrate that the ratio of the maximum stress applied to the final stress after relaxation of the coal-tar mixtures tended to range from 40 to 60 percent. This relationship was similar for both aged and non-aged coal-tar mixtures and at temperatures of 23 °C (73 °F) and 44 °C (111 °F). A series of confined, stress-relaxation tests were performed on an airfield HMA mixture using AC-20 asphalt. These tests were performed with confining pressures of (40 and 90 psi) and at a temperature of 60 °C (140 °F). The ratio of the maximum stress applied to the final stress after relaxation was almost identical for both confining pressures, about 57 percent (Hodo 2001). This would indicate, at least for the conditions tested and prior to aging of the HMA, the coal-tar sealer and the underlying HMA would have similar stress-relaxation properties. These tests did not reveal what affect aging or hardening of the HMA would have on these properties. However, other research has shown that aging decreases the slope of the relaxation curve that would result in a slower decrease in residual stress or relaxation of the HMA (Daniel et al. 1998). Exact values cannot be determined; however, aging of the HMA would result in an increase in the ratio of retained stress. Therefore, at least at higher temperatures, it would appear that both the underlying HMA and the coal-tar sealer will relax or release stress at similar rates and would not develop substantial residual stress between them.

SUMMARY

Movement in the coal-tar sealer that results in the development of tensile stresses is caused mainly by temperature variations. Under service conditions, the

coal tar mixtures age, and the tensile stresses developed increase with this aging for a given range of movement. Under the same conditions, the HMA, because it has been sealed and protected, will not experience significant changes in material properties. The literature and the results of this study show that a cured coal-tar sealer is less temperature susceptible than a HMA pavement.

Cracking occurs in the coal tar sealers when the tensile stresses developed exceed the tensile strength of the sealer. Evaluation of the amount of stress developed from thermal movements alone suggests that the stresses achieved would not exceed the tensile strength of the sealers. The shrinkage due to the loss of volatiles must therefore also be a contributing factor. It would appear that a mechanistic type model is inadequate at this stage such that a mechanistic design approach is impractical. The selection of a coal-tar treatment must therefore rest in an empirical/experienced-based approach.

CHAPTER 7: DEVELOPMENT OF AN EXPERT SYSTEM FOR COAL-TAR SEALERS

INTRODUCTION

As a mechanistic design procedure is not viable the selection of an appropriate coal-tar sealer mixture could be approached using an expert system. An exact definition of an expert system does not exist; however, they all simulate or use an expert's knowledge and experience in solving some problem. When knowledge of a subject is incomplete, the judgment of an expert is required (Masri and Moore 1995). This is generally accomplished by using an information database provided by an expert in the particular field of interest, plus rules for interpretation of the data in terms of the problem or goal within the scope of the system (Siddall 1990). The expert system can also be called a knowledge-based system and it is usually considered a form or application of artificial intelligence (Siddall 1990).

The basis of an expert system is the use of an intuitive decision making procedure to assist a non-expert in arriving at the desired solution. This intuitive decision-making process makes use of IF/THEN rules or statements to achieve a solution. Empirical or physical modeling knowledge or results can be incorporated into the system at any time. In this case the goal is for a non-expert engineer/designer to correctly select the proper coal-tar sealer mixture and to develop a satisfactory construction specification based on the guide specification given in Appendix D.

INFLUENCES ON SYSTEM FROM STUDY

Conventional testing, as detailed in Chapters 4 and 5, showed that fuel resistance and freeze-thaw testing could provide useful information, while the viscosity test did not directly provide information useful to design or construction. The evaluation of the fuel resistance of various mixtures resulted in a limiting in the amount of aggregate allowed within a mixture. The fuel resistance testing showed that the amount of aggregate used in the coal-tar sealer mixtures should not exceed 0.36 to 0.60 kg of aggregate per liter (3 to 5 lb of aggregate per gallon) of coal-tar emulsion. This amount is somewhat increased if a polymer is used in the mixture. Evaluation of the freeze-thaw tests indicated that the test method could be used to judge the durability of the coal-tar sealer mixture. One important feature of the test is that during specimen preparation the overall suitability of the coal-tar mixture components can be evaluated. If any imperfections form in the surface of the freeze-thaw specimens, the mixture components should be changed or adjusted until the imperfections no longer develop. If the components cannot be mixed and applied in a smooth, uniform manner the sealers will not form a durable surface.

The non-conventional testing, as detailed in Chapters 4 and 5, did not provide directly implementable test methods for coal-tar sealers. However, it did provide useful information regarding the processes involved in cracking. Uniaxial testing and the curing/aging of the mixtures showed that the mixtures got stiffer with time as they lost weight through evaporation. The testing also showed that the addition of polymer to a mixture allowed for increased yielding of the specimen prior to failure (ductile). Stress-relaxation testing showed that coal tar mixtures tended to retain higher stress

levels than HMA, especially at higher temperatures. The curing/aging testing of both field- and laboratory-cured mixtures showed that mass loss would decrease with time to an asymptotic value. The time required depends upon the curing/aging conditions present. Through oven curing of a few days, specimens could be aged to have the same tensile properties of those that had been aged for many months. Coal-tar sealers evidence aging through increased mixture stiffness, such as that showed in BBR test results, Table 5.7. Comparison of tensile tests on field and oven-cured specimens indicated that coal-tar sealers age to a given condition within a relatively short period of time and then experience only minor change thereafter. The thermal analysis showed that for a given change in temperature a coal-tar sealer would expand or contract more than the underlying HMA. The dynamic shear rheometer testing showed that there were definable differences between the base coal tars. However, the DSR device was not able to test cured sealer.

SYSTEM FEATURES

The expert system leads an engineer/designer through a series of questions concerning the planned project. Depending upon the answers selected for each question, adjustments to the guide specification are developed following the procedure outlined in Figure 7.1. The system will provide a printout of recommended mixture design requirements that can be provided to a contractor to develop a final design. The guide specification is provided in Word format at the start of the system to allow an engineer/designer, who does not want to use the expert system, to go directly this standard specification without modification.

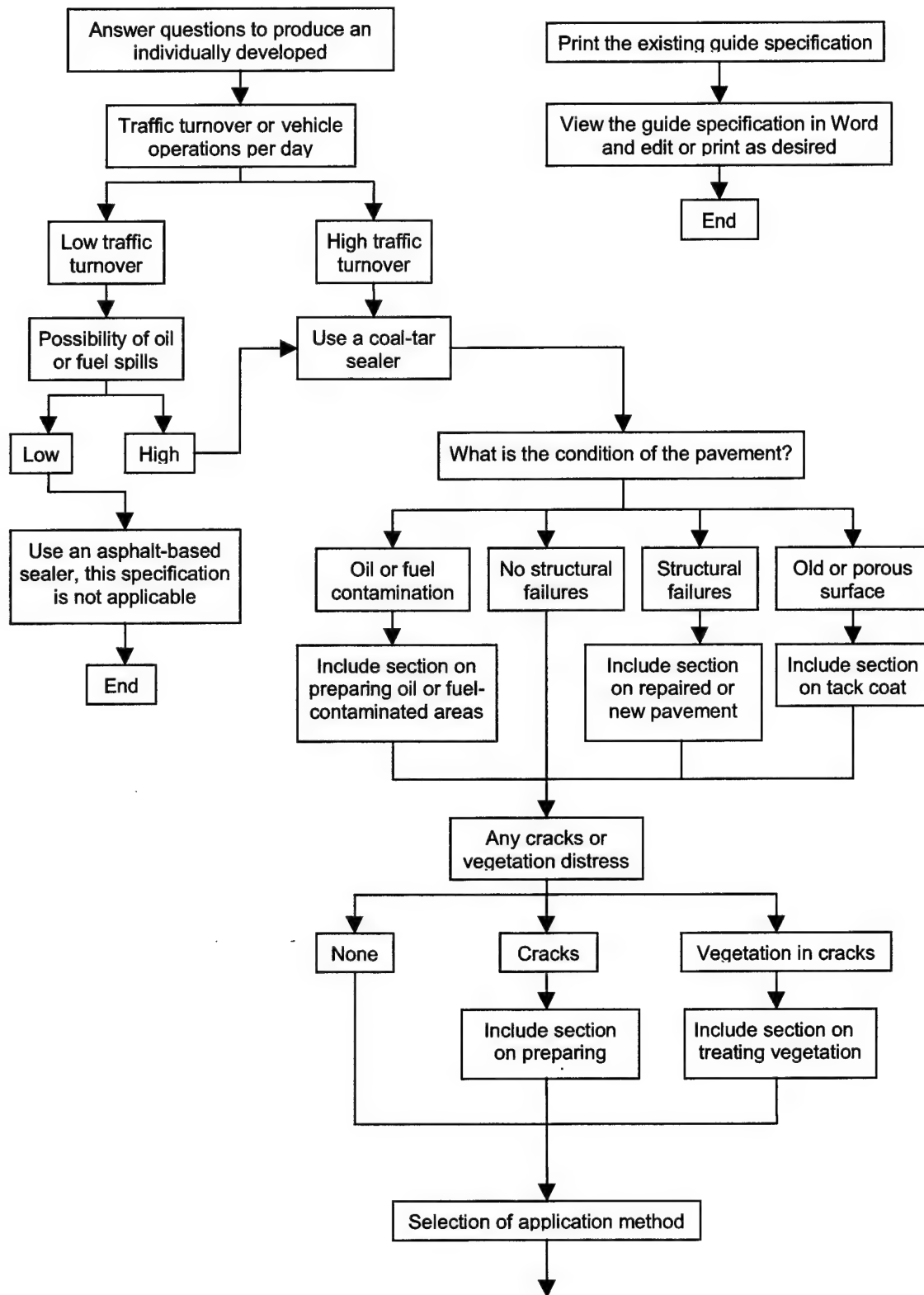


Figure 7.1 Flow chart for coal-tar sealer expert system (Sheet 1 of 3)

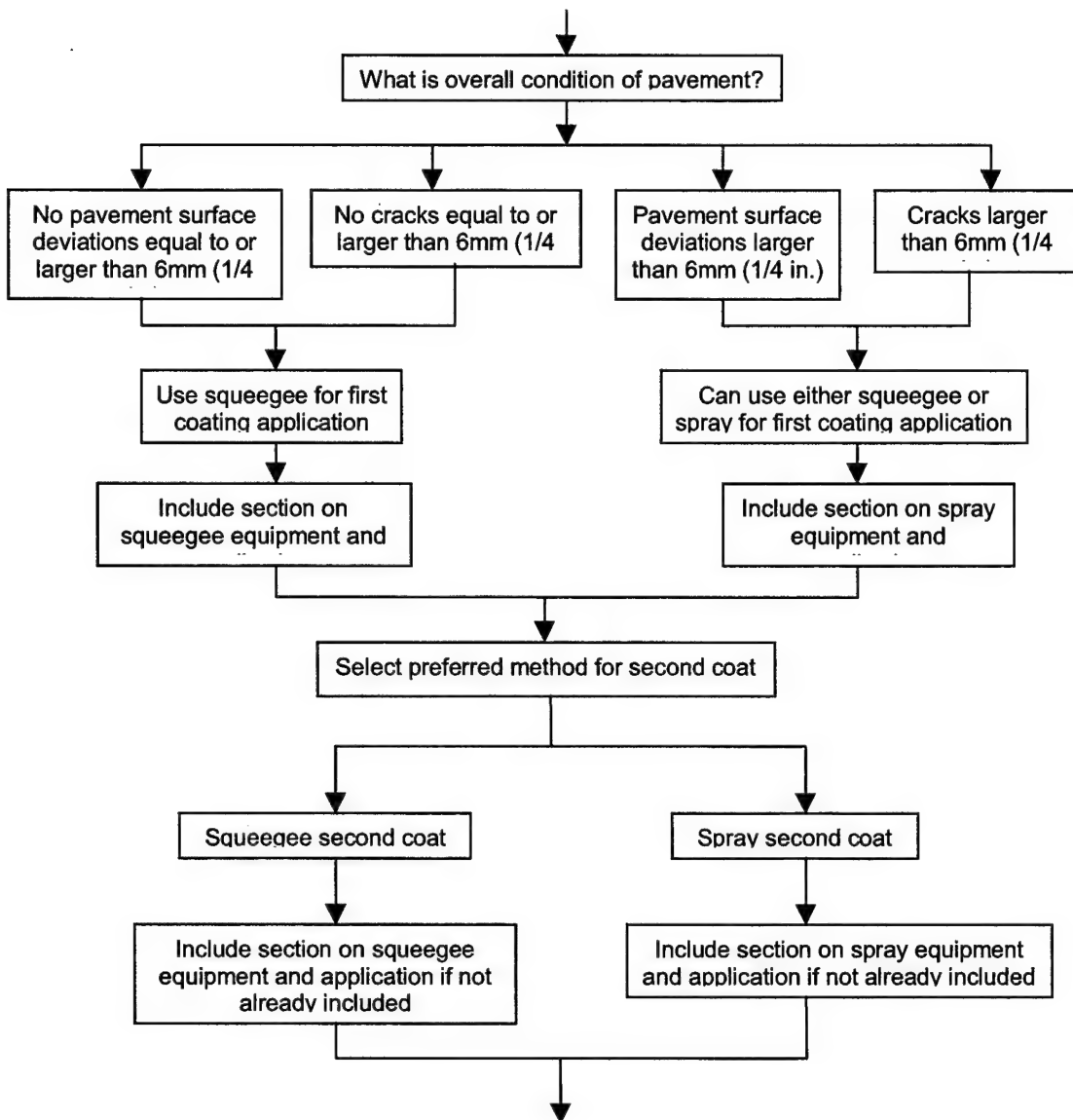


Figure 7.1 (Sheet 2 of 3)

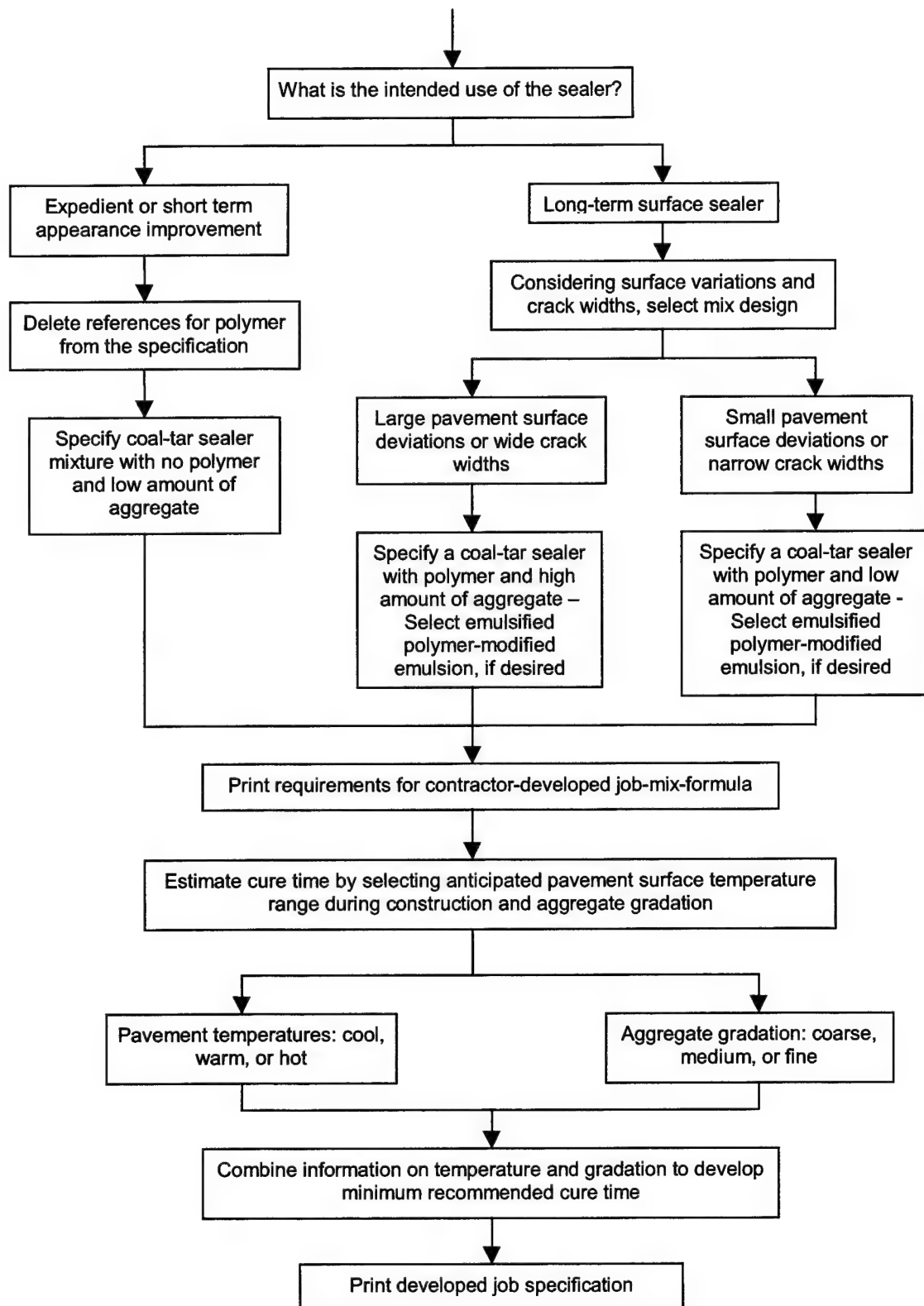


Figure 7.1 (Sheet 3 of 3)

System Software

The expert system was developed using Visual Basic 6.0 software. The completed program can be converted to an executable file that can be run on any windows-based operating system. The expert system occupies approximately 360 KB of space and can therefore be conveniently placed on a 1.2 MB disk. A disk is attached.

The various screens used to query the engineer/designer for the development of the specification and pertinent notes are given in Appendix E. Along with each screen, the visual basic code that pertains to each screen is also listed.

Inputs

A flow chart illustrating the basic progression of decisions required by the expert system is given in Figure 7.1. The basic inputs are summarized and a general cross-reference to what section of the study influenced them is given as follows:

- Amount of traffic expected – Chapters 2 and 3 (need for coal tar)
- Expectation of fuel spill – Chapters 2 and 3 (need for coal tar)
- Use of coal-tar sealer – Chapters 2, 3, 4, and 5 (use coal tar only for fuel resistance)
- The condition (oil or fuel contamination, structural condition, and old or porous surface) of the existing pavement – Chapters 2 and 3 (literature and field placement)
- Any cracks or vegetation in the cracks – Chapters 2 and 3 (literature and field placement)
- Application method, squeegee or spray – Chapters 2 and 3 (application of sealers)

- Long-term or expedient application – Chapters 2, 3, 4, and 5 (requirements and need for durability)
- Mixture design
 - Requirements
 - Drying time – Chapters 2 and 3 (application of mixtures)
 - Resistance to kerosene – Chapters 2, 4, and 5 (fuel resistance testing)
 - Freeze-thaw resistance – Chapters 2, 4, and 5 (freeze-thaw testing)
 - Gradation – Chapters 2, 3 (literature and application of mixtures)
 - Polymer – Chapters 3, 4, and 5 (application and performance of mixtures)
- Curing time (Anticipated climatic conditions and aggregate size) – Chapters 3, 4, and 5 (curing of coal-tar emulsions during construction and specimen preparation)

Outputs

The output from the expert system will be a construction specification in Word format. The output document obtained will vary in content in regards to the responses provided to the system. If desired, the complete unedited guide specification is available in Word format. These Word documents can be further edited or modified as required for local conditions or preferences. The final specification can then be printed or used in electronic form.

SUMMARY

An expert system was developed to produce construction specifications and mixture design recommendations for coal-tar sealers. The engineer/designer is prompted to answer questions regarding climatic and pavement conditions and the anticipated traffic on the pavement to be sealed. The engineer/designer is provided

guidance where selections are required. The system can be transported on a 1.2 MB disk and will run on any windows based operating system. The output construction specification is in Word format, allowing for any additional editing or adjustments for local conditions or requirements.

CHAPTER 8: CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

The following conclusions are based upon a literature review, field test section performance, laboratory evaluation of materials, and the development of an expert system. The coal-tar emulsions, base coal-tar materials, and polymer additives used in this study were obtained from two manufacturers. One type of polymer (the most common type used commercially), supplied by each manufacturer for his emulsion, was used in the evaluation. Silica sand, of a gradation historically used by the military for fuel-resistant seal coats, was used in all mixtures containing aggregate. Specifically, the following are the conclusions, with pertinent chapters in brackets, which can be drawn from this study:

- (2 and 3) Coal tar emulsions can be used safely, provided some simple safety provisions are followed.
- (3) The darker color of the coal-tar sealed pavement increased the temperature of those sections in relation to the surrounding unsealed pavement. This increase in temperature approached 6°C (11°F) on sunny days.
- (2 and 3) Coal tar emulsion sealers generally develop at least some hairline cracks within a year after placement. These cracks gradually widen and spread throughout the sealed surface until it is no longer effectively protecting the pavement surface. These cracks occur in all types of climates, even where freezing temperatures are never or almost never encountered. The useful life of coal-tar sealers would appear to range from 3 to 5 years.

- (3) Increased aggregate within sealer mixtures effectively increased the time until first cracks formed in the various sealer mixtures.
- (3 and 5) The use of a polymer additive generally provided improved field performance or less cracking when compared to non-modified coal-tar materials. The addition of a polymer to a mixture increases its viscosity (thickening) and allows particles (aggregate) to remain in suspension; therefore, more aggregate can be added to the mixture. The addition of polymer in increasing amounts allows more aggregate to be placed in a mixture while maintaining fuel resistance.
- (5) The fuel resistance and CE-modified freeze-thaw test methods should form part of the basis for the selection of a coal-tar sealer mixture. If the selected mixture is not fuel resistant it is completely unacceptable. The preparation and evaluation of freeze-thaw samples allows for a visual observation and rejection of incompatible mixture components and indication of long-term mixture durability.
- (2 and 5) Viscosity testing as a mixture design criteria is not recommended. This is due to the relatively wide range of viscosity over which sealers can be applied and the difficulty in obtaining accurate viscosity readings.
- (3, 4, and 5) Due to the colloidal system used to emulsify coal tar, coal-tar sealer mixtures cannot be molded directly, but must be poured onto a flat surface and allowed to cure. Through a series of saw cuts, individual test specimens for Bending Beam Rheometer and uniaxial tension tests were fabricated. The test results varied widely, which limit their usefulness to trends and not detailed analysis. The variable test results could be attributed to imperfections developed

during casting and curing and because specimen dimensional inputs were measured with calipers.

- (5) The Bending Beam Rheometer tests on sealer mixtures, both with and without aggregate, showed increased creep stiffness with time. Tests also showed that increasing the amount of polymer or decreasing the amount of aggregate resulted in lower creep stiffness.
- (5) DSR evaluation of coal-tar emulsions was not possible because of the cured properties of the emulsions. Testing of the base coal tars from which the emulsions were produced showed a high temperature susceptibility and that the base coal tar used to make mixtures 1 through 6, which overall had better field performance, was not as stiff when compared to the other coal tar.
- (5) Uniaxial tension testing showed that for laboratory-cured specimens the coal tar from manufacturer No. 2 had higher tensile stress values. The amount of aggregate only caused a significant difference for field-cured specimens at 23°C (77°F), where the specimens containing the higher amount had an increased in tensile stress. An increase in temperature resulted in decreased tensile stress for all mixtures. However, it was not significantly different for the laboratory-cured specimens with high aggregate content. At 23°C (77°F), polymer caused a decrease in tensile stress at a 3 percent level and an increase at the 7 percent level. At 44°C (111°F), polymer decreased the tensile stress for specimens containing lower amounts of aggregate and did not have a significant effect on those containing higher amounts of aggregate. Aging of the mixtures produced significantly higher tensile stresses at both temperatures

- (5) Stress-relaxation testing showed that in most mixtures the level of stress generally decreased rapidly to about 40 to 60 percent of the initial stress value. The source of the coal tar had no significant effect on the level of stress achieved. At 23 °C (73 °F) the field-cured mixture with a higher amount of aggregate had an increased normalized stress value, while at 44 °C (111 °F) the field-cured low aggregate mixture had an increased stress value. The effect of temperature was only significant for the field-cured high aggregate mixture where an increase in temperature lowered the stress value. At 23 °C (73 °F), the addition of polymer lowered the normalized stress values for all field- and laboratory-cured mixtures and the decrease was significant for all mixtures except mixture F5. At 44 °C (111 °F), only one field- and laboratory-cured mixture (F6) was significantly different from the mixture without polymer. The aged specimens had higher normalized stress values, although they were not significantly greater in all cases.
- (2 and 5) Coal tar materials, and in particular Road Tar from which coal-tar emulsions are manufactured, age and harden mainly by evaporation of volatile components. This would indicate that the aging or hardening would occur faster in areas with higher temperatures. Coal-tar emulsion mixtures cure/age through initial water loss (generally within 24 hours) and then continue to lose mass through evaporation for an extended time period (years) depending upon curing conditions. The addition of polymer to coal-tar mixtures reduced the mass loss, while varying the amount of polymer did not effect the rate of mass loss.
- (5) Aging of coal-tar mixtures in an oven at 75°C (167°F) for about 5 days will stabilize the mass of the specimens and, depending upon the mixture, provide

tensile strengths equivalent to those of specimens field aged for about 6 to 8 months.

- (5) The coefficient of thermal expansion of the cured coal-tar emulsion mixtures was about 1.5 to 3 times greater than the underlying hot-mix asphalt.
- (7) An expert system was developed, utilizing the findings of this study that allows for a non-expert to develop a suitable construction specification for coal-tar sealers. The engineer/designer is prompted to answer questions regarding climatic and pavement conditions and the anticipated traffic on the pavement to be sealed. The engineer/designer is provided guidance where selections are required.

RECOMMENDATIONS

- Specimen preparation and test method procedures could be used to evaluate the effectiveness of different polymer materials in improving the performance of coal-tar sealers. A manufacturer should be sought who would be willing to evaluate several different polymers to improve fuel resistance and durability properties.
- The use of the bending beam rheometer should be further investigated towards the goal of reducing result variability. If the variability can be reduced it could be useful in defining a level between acceptable and unacceptable performance of various mixtures, with the goal of using it as a performance based test method.
- A dynamic material analyzer (DMA) device could test rectangular shaped specimens of cured coal-tar sealer at a frequency comparable to the low rates of strain found in field applications. The simplification in specimen fabrication (rectangular versus dog-bone shapes required in this study) should help reduce the variability of the results and would also allow for an increased number of replicate

tests. The DMA could provide a method of developing criteria for selecting a superior performing sealer and could become a performance based test method.

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APPENDIX A
BROOKFIELD VISCOSITY PROCEDURE

BROOKFIELD VISCOSITY

1. Apparatus

- a. Brookfield digital viscometer (model DV-II+) and stand.
- b. Number 27 spindle for HB DV-II+ model viscometer.
- c. Paint cans: 1-quart capacity.

2. Sample preparation

- a. Allow components (coal tar emulsion, water, and additive) to reach ambient laboratory temperature $23\pm 3^{\circ}\text{C}$ ($73\pm 5^{\circ}\text{F}$).
- b. Mix coal-tar emulsion and other components, as required, in container specified in apparatus with 50 strokes of a large laboratory-mixing spoon.
- c. When adding additional components to the mixture, stir with an additional 50 strokes of the mixing spoon.

3. Procedure

- a. Fill the quart paint can as specified in 1a, with desired material components to allow for complete immersion of the spindle in accordance with 2a through 2c.
- b. Insert spindle No. 27 in the material until the mixture level coincides with the immersion groove on the spindle shaft.
- c. Avoid trapping air bubbles underneath spindle.
- d. Adjust rotational speed on Brookfield viscometer to 20 revolutions per minute (rpm).
- e. Start motor and record viscosity value in centipoise or poise after five seconds of rotation. If the viscosity reading is too low for spindle 3, repeat procedures 3a through 3e using spindle No. 1.
- f. Add aggregate to the total liquids with 50 strokes of large laboratory mixing spoon.
- g. Repeat procedure 3a through 3e when adding additional components to the mixture.

4. Report

- a. Date of test and complete identification of the coal tar mixture formulation tested.

- b. Spindle number and rpm setting.
- c. Temperature of sample tested (if performed out of prescribed range).
- d. Viscosity of total liquids in centipoise or poise.

APPENDIX B

CYCLIC FREEZE THAW CONDITIONING MODIFIED FAA TEST PROCEDURE

1. Scope

This method covers the analysis of crack development in a composite rubberized coal tar emulsion seal coat when exposed to multiple cycles of freezing and thawing.

2. Apparatus

- a. 305 × 305 mm (12 × 12 in.) square 16 gauge (1.52 mm (0.0598 in.)) sheet metal mask with a 280 × 280 mm (11 × 11 in.) square center removed.
- b. 305 × 305 mm (12 × 12 in.) square section of a granulated roofing felt (standard asphalt roofing shingle).
- c. Oven capable of maintaining 60°C (140°F).
- d. Freezer capable of maintaining -12°C (10°F).

3. Procedure

- a. Using mask described in 2a, apply uniform thickness of the coal tar emulsion mixture to the rough side of the roofing shingle described in 2b.
- b. Allow material to cure at 25±1°C (77±2°F) and 50±10 percent relative humidity for 24 hours.
- c. Place sample in the 60°C (140°F) oven for 24 hours.
- d. Remove sample and record crack development.
- e. Submerge the sample in water for one hour.
- f. Place sample in -12°C (10°F) freezer for 24 hours.
- g. Remove from freezer; this constitutes one freeze-thaw cycle.
- h. Repeat procedures 3c through 3f for a total of 10 cycles.
- i. Inspect the samples after 5 and 10 cycles and rate the cracking in accordance with the following scale and the following procedure:

- (1) Using a commercially available thickness gauge, estimate the width of the largest crack appearing on the surface.
- (2) Next, place a grid frame over the coal tar seal coated shingle (after freeze/thaw conditioning). The grid is a wood frame with an inside diameter of 300 × 300 mm (12 × 12 in.). A grid is formed across the inside opening of the frame by subdividing the opening into 10 equal divisions both horizontally and vertically with twine anchored to the frame. This will provide 100 equally sized squares.
- (3) Count the number of squares in which a crack occurs. The percent cracking is equal to the number of squares.
- (4) Compare the results to table below:

Severity of Cracking	Width of Widest Crack	Percent of Cracking
Hairline	0.010 mm	NA – Cracks are barely visible
Slight Cracking	0.015 mm	< 25 percent
Moderate Cracking	0.020 mm	> 25 percent
Severe Cracking	0.020 mm or greater	> 50 percent
0 – No cracking, 1 – Hairline cracking, 2 – Slight cracking, 3 – Moderate cracking, 4 – Severe cracking		

4. Report

- a. Report the crack rating at 5 and 10 cycles.
- b. Mixture Acceptance Criterion: Rating of 1 or less at 5 cycles and 3 or less at 10 cycles is required for an acceptable mixture.

Note: A mixture is not suitable for testing when cracking occurs prior to any testing cycles.

APPENDIX C

CYCLIC FREEZE THAW CONDITIONING CORPS OF ENGINEERS MODIFIED FAA TEST PROCEDURE

1. Apparatus

- a. 305 × 305 mm (12 × 12 in.) square 16-gauge (1.52 mm (0.0598 in.)) sheet metal mask with a 250 × 250 mm (10 × 10 in.) square center removed.
- b. 305 × 305 mm (12 × 12 in.) square section of a granulated roofing felt (standard asphalt roofing shingle).
- c. Oven capable of maintaining 60°C (140°F).
- d. Freezer capable of maintaining -12°C (10°F).

2. Procedure

- a. Make 3 specimens for each mixture tested.
- b. Using mask described in 1a, apply uniform thickness of the coal tar emulsion mixture to the rough side of the roofing shingle described in 1b.
- c. Allow material to cure at ambient laboratory temperature 23±3°C (73±5°F) and 50±10 percent relative humidity for at least 48 hours.
- d. Note the surface of each specimen, if a consistent surface texture was not achieved the mixture should be rejected for non-compatibility. The mixture should be retested one time to make sure that no mistakes in composition occurred to cause the failure.
- e. Place sample in the 60°C (140°F) oven for 18 hours.
- f. Remove from oven and submerge the sample in water for one hour.
- g. Remove from the water and allow excess water to drain off by holding the sample vertically for 30 – 40 seconds, then place sample in -12°C (10°F) freezer for 4 hours.
- h. Allow about 1 hour for evaluation and movement of the sample between the oven, water, and freezer.
- i. Repeat procedures 2c through 2f for a total of 10 cycles.
- j. Inspect the samples after 5 and 10 cycles and rate the cracking in accordance with the following scale and the following procedure:
 - (1) Using a commercially available thickness gauge, estimate the width of the largest crack appearing on the surface.

- (2) Next, place a grid frame over the coal tar seal coated shingle (after freeze/thaw conditioning). The grid is a wood frame with an inside diameter of 250 × 250 mm (10 × 10 in.). A grid is formed across the inside opening of the frame by subdividing the opening into 10 equal 25 mm (1 in.) divisions both horizontally and vertically with twine anchored to the frame. This will provide 100 equally sized squares.
- (3) Count the number of squares in which a crack occurs. The percent cracked area is equal to the number of squares.
- (4) Determine a Crack Severity Value (CSV) by multiplying the width of the largest crack by the percentage of cracked area.
- (5) Compare the results to table below:

Severity of Cracking	Crack Rating	Crack Severity Value Ranges
None	0	0
Slight Cracking	1	>0 - ≤1
Low Cracking	2	>1 - ≤3
Moderate Cracking	3	>3 - ≤5
Heavy Cracking	4	>5 - ≤8
Severe Cracking	5	>8

3. Report

- a. The average (of three tests) crack rating at 5 and 10 cycles.
- b. Mixture Acceptance Criterion: Rating of 1 or less at 5 cycles and 3 or less at 10 cycles is required for an acceptable mixture.

Note: A mixture is not suitable for testing when it does not achieve a consistent surface texture or contains cracking or surface tears occur prior to any testing cycles.

APPENDIX D
COAL-TAR SEALER
GUIDE SPECIFICATION

GUIDE SPECIFICATION FOR CONSTRUCTION

FUEL-RESISTANT (COAL TAR) SEALER

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 - 1.2.2.2 Additive Materials**
 - 1.2.2.3 Aggregate**
 - 1.2.3 Payment**
- 1.3 SUBMITTALS**
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PART 2 PRODUCTS

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-- End of Section Table of Contents --

GUIDE SPECIFICATION FOR CONSTRUCTION

FUEL-RESISTANT (COAL TAR) SEALER

NOTE: This guide specification covers the requirements for fuel-resistant (coal tar) sealer for bituminous pavements in parking and maintenance areas.

PART 1 GENERAL

1.1 REFERENCES

NOTE: Issue (date) of references included in project specifications need not be more current than provided by the latest change (Notice) to this guide specification.

The publications listed below form a part of this specification to the extent referenced. The publications are referred to in the text by basic designation only.

AMERICAN SOCIETY FOR TESTING AND MATERIALS (ASTM)

ASTM C 136	(1996a) Sieve Analysis of Fine and Coarse Aggregates
ASTM C 142	(1978; R 1997) Clay Lumps and Friable Particles in Aggregates
ASTM D 75	(1987; R 1997) Sampling Aggregates
ASTM D 140	(2000) Sampling Bituminous Materials
ASTM D 2939	(1998) Emulsified Bitumens Used as Protective Coatings
ASTM D 5727	(1998) Emulsified Coal-Tar Pitch (Mineral Colloid Type)

1.2 UNIT PRICES

NOTE: Delete this paragraph when lump sum bidding
is used.

1.2.1 Waybills and Delivery Tickets

Copies of waybills and delivery tickets shall be submitted during the progress of the work. Before the final statement is allowed, the Contractor shall submit certified waybills and delivery tickets for all materials used in the work covered by this section. The Contractor shall not remove remaining coal-tar emulsion, additive, or aggregate until measurements of the quantities used have been made.

1.2.2 Method of Measurement

NOTE: When other methods of measurement are
desired or necessary, this paragraph will be modified
accordingly.

1.2.2.1 Coal-tar Emulsion

The amount of coal-tar emulsion to be paid for will be measured by the number of liters [gallons] of the material used in the accepted work. The proper coefficient of volumetric expansion per degree C, [F,] as supplied by the manufacturer, shall be used for all binder volume calculations.

1.2.2.2 Additive Materials

Additive materials include any additives or modifiers added to the coal-tar sealer mixture. The materials may be measured by volume or weight.

1.2.2.3 Aggregate

The amount of aggregate to be paid for will be the number of dry metric tons (2,000 pound tons) placed and accepted as part of the coal-tar sealer mixture in the completed work.

1.2.3 Payment

Quantities of coal-tar sealer, additives, and aggregate determined as specified will be paid for at the respective contract unit prices. Such payment will constitute full compensation for all operations necessary to complete the work as specified herein.

1.3 SUBMITTALS

NOTE: Submittals must be limited to those necessary for adequate quality control. The importance of an item in the project should be one of the primary factors in determining if a submittal for the item should be required.

Submittals must be approved by the Contracting Officer prior to the start of the project. The following shall be submitted in accordance with Section 01330
SUBMITTAL PROCEDURES:

SD-06 Test Reports

Mix Proportions; [_____].

A copy of the mixture proportions that meet all the requirements of this specification.

Sealer Materials; [_____].

Samples or certified test results of the materials, [_____] days prior to the beginning of work. No material will be used until it has been approved.

1.4 EQUIPMENT

Machines, tools, and equipment used in the performance of the work will be approved before the work is started and shall be maintained in satisfactory condition.

1.4.1 Mixing

Mixing of the sealer shall be accomplished in a mobile batch mixer of a type approved by the Contracting Officer. The mixer shall be capable of producing a uniform mixture of coal-tar emulsion [, additives,] and aggregate. The mixing unit shall have suitable mixing blades to combine the predetermined quantities of materials into a homogeneous slurry.

1.4.2 Application

NOTE: A decision must be made to apply the sealer by spraying or by squeegeeing, based partially upon the condition of the pavement prior to sealing.

Manufacturer's recommendations should be followed when determining the method of application. Spraying applies an even distribution of material throughout the application area. Application with a squeegee will allow for the filling of slight imperfections, depressions, or cracks. When desired, the initial squeegee application may be followed by a second spray application.

The following paragraphs should be edited depending upon the application method selected.

1.4.2.1 Squeegee Application

A variable-width mechanical-type squeegee shall be attached to the mobile-application vehicle to place the slurry. The attached squeegee shall be maintained with flexible material in contact with the pavement surface to control application and prevent excessive loss of sealer mixture from the spreader on varying grades and crown. The squeegee shall be capable of adjustments to ensure a uniform spread, and the mobile-application vehicle shall discharge the sealer to provide satisfactory application. The vehicle shall be provided with a water tank, pump, and spray bar for fogging the pavement surface ahead of the spreader box. The spreader box shall be kept clean, and buildup of sealer and aggregate on the squeegee and spreader box shall not be permitted.

1.4.2.2 Spray Application

The spray vehicle may be self-propelled or towed, designed and equipped to apply a uniform mixture of sealer and aggregate at rates ranging from 0.45 to 3.17 liters per square meter [0.10 to 0.70 gallons per square yard]. Sprayer equipment shall include a separate power unit, agitated tank, spray bar, hand spray wand, and suitable pump and plumbing for handling sealer and aggregate.

1.4.3 Cleaning Equipment

Cleaning equipment shall consist of power brooms, power blowers, power vacuums, air compressors, hand brooms, and other equipment as needed. The equipment shall be suitable for cleaning the surface and cracks in the existing pavement.

1.4.4 Hand Tools

Hand tools shall consist of hand squeegees, shovels, and other equipment as necessary to perform the work.

1.5 SAMPLING AND TESTING

1.5.1 Sampling

Aggregate samples shall be furnished in accordance with ASTM D 75. Samples of coal-tar emulsion, unless otherwise specified, shall be in accordance with ASTM D 140. Additional samples of materials shall be furnished as required.

1.5.2 Testing

NOTE: An approved testing laboratory is required to meet the testing requirements of this specification. The Contractor testing, when accepted, should only be used for quality assurance on the job and not for the initial mixture design.

Coordinate this paragraph with the specified requirements in paragraph Composition.

Materials shall be tested to establish compliance with the specified requirements. Quality assurance testing shall be performed by an approved commercial testing laboratory or by Contractor testing, subject to approval by the Contracting Officer.

1.5.3 Calibration Test

NOTE: Calibration of all equipment used to place sealer will allow the Government to determine the application rate and thereby the total quantity of material placed per unit area of pavement.

Equipment, materials, and labor shall be furnished as necessary to calibrate equipment used to place the sealer. Calibrations shall be made with the approved job materials prior to applying the sealer materials to the prepared surface. The manufacturer shall provide a method of calibration for all commercial equipment.

1.5.4 Trial Application

Prior to applying the sealer mixture, the Contractor shall place a test section at least 30 meters [100 feet] long and two squeegee widths wide using the approved materials and equipment. The sealer mixture shall be placed in accordance with the specified requirements. The rate of application shall be determined for compliance to specification requirements. If the test section does not conform to the specification requirements, necessary adjustments shall be made, and additional test sections shall be constructed at the Contractor's expense for conformance to the specifications. Where test sections do not conform to the specification requirements, the sealer mixture shall be removed by milling, grinding, or another approved method. Test sections that conform to all specification requirements may become part of the accepted sealed surface.

1.6 DELIVERY AND STORAGE

Materials delivered to the site shall be inspected for contamination and damage, unloaded, and stored with a minimum of handling. Aggregates shall be covered or stored to keep them dry. The coal-tar emulsion shall be stored according to the manufacturer's recommendations. Materials determined by the Contracting Officer to be contaminated, damaged, or which fail to meet specification requirements shall be removed from the job-site and replaced at no additional cost to the Government.

1.7 WEATHER LIMITATIONS

Sealer shall not be applied if air or pavement temperatures are below 10 degrees C [50 degrees F] or if there is any possibility that the sealer will freeze before it has cured, unless otherwise directed by the Contracting Officer. No sealer shall be placed when rain or other impending weather conditions will prevent proper curing of the sealer mixture.

PART 2 PRODUCTS

2.1 AGGREGATE

NOTE: All of the gradations given below in Table 1 can produce a satisfactory sealer mixture. Generally, the larger the aggregate particles in the mixture are, the

coarser or more skid resistant the final surface is. The selection of a gradation should be based on recommendations from the coal-tar emulsion manufacturer.

Table 1 lists the suggested minimum application rates for the three aggregate gradation ranges. These rates are based on the mixture requirements to embed the largest aggregate particle to at least one-half its thickness.

The aggregate shall be either a natural or manufactured angular aggregate and shall be composed of clean, hard, durable, uncoated particles free from clay and other objectionable material when tested in accordance with ASTM C 142. The aggregate shall fall within one of the gradation ranges given in Table 1, when tested in accordance with ASTM C 136. The actual gradation can fall anywhere within the types listed, provided that at least 70 percent of the aggregate falls within two consecutive sieve sizes as given in Table I.

TABLE I. AGGREGATE GRADATION RANGES AND CORRESPONDING MINIMUM SEALER MIXTURE APPLICATION RATES

Sieve Size	Percent Passing		
	Coarse	Medium	Fine
1.18 mm (No. 16)	100	100	100
0.850 mm (No. 20)	85-100	98-100	100
0.600 mm (No. 30)	25-85	85-100	98-100
0.425 mm (No. 40)	5-25	25-85	85-100
0.300 mm (No. 50)	2-10	5-25	25-85
0.212 mm (No. 70)	--	2-10	5-25
0.150 mm (No. 100)	0-2	0-4	2-10
0.106 mm (No. 140)	--	0-2	0-2
Minimum sealer mixture application rate liter/square meter (gallon/square yard)	1.36 (0.30)	0.91 (0.20)	0.68 (0.15)

2.2 WATER

The water added to the sealer mixture shall be potable. The temperature of the water added during mixing shall be at least 10 degrees C [50 degrees F].

2.3 COAL-TAR EMULSION

The base coal-tar emulsion (mineral colloid type) shall meet the requirements of ASTM D 5727.

2.4 POLYMER ADDITIVE

NOTE: Delete this paragraph when a polymer additive or any other modifier is not to be used in the coal-tar sealer mixture. The most common type of polymer material used for coal-tar sealers is an acrylonitrile-butadiene rubber. This polymer is supplied as an emulsion. The polymer emulsion must be compatible with the coal-tar emulsion and is therefore usually supplied by same manufacturer.

The polymer additive used shall be the type and make as recommended by the coal-tar emulsion manufacturer.

2.5 SEALER MIXTURE

NOTE: The mixture components can be the same for either squeegee or spray applications. The resistance to kerosene test (ASTM D 2939) will limit the amount of aggregate that can be added per gallon of emulsion. The use of a polymer has not shown to give improved performance in all instances. The polymer will increase the viscosity of the sealer mixture; however, allowing more aggregate to be held in suspension. The amount of polymer additive, if used, should usually range from 1 to 3 liters (gallons) per liter (gallon) of coal-tar emulsion. The amount of aggregate should range from 0.24 to 0.60 kg per liter (2 to 5 lb per gallon) of emulsion.

The exact proportions of coal tar, water, [polymer additive,] and aggregate to be used in the preparation of the sealer shall be determined by laboratory mix design and shall be furnished by the Contractor from a laboratory approved by the Contracting Officer. The sealer mixture shall meet the requirements as specified in

Table 2. The sealer components shall be mixed to produce a homogeneous mixture that adequately suspends the aggregate in the mix.

TABLE II. PHYSICAL PROPERTIES OF SEALER MIXTURES

<u>Property</u>	<u>Requirement</u>	<u>Referenced Test Method</u>
Drying time, firm set	8 hours maximum	ASTM D 2939
Resistance to Kerosene	No penetration or loss of adhesion	ASTM D 2939
Freeze-Thaw Resistance	Rating of 3 or less after 10 cycles	Appendix C: CE Modified FAA Test Procedure

PART 3 EXECUTION

NOTE: Traffic marking paint need not be removed from streets, roads, or parking areas unless the paint is loose and flaking off. Large painted areas, such as those that occur on airfield pavements, may have to be removed prior to applying the sealer mixture to obtain satisfactory bond to the pavement. If paint removal is not required, the reference to paint removal in this paragraph will be deleted.

Scrubbing with detergents cannot satisfactorily clean asphalt pavements that are heavily saturated with oil or grease. Although a clean surface may be obtained, the oil and grease below the surface will migrate to the top and will bleed through the sealer mixture, or will cause the sealer mixture to lose bond to the pavement. When the amount of contaminants is not severe, the surface of the pavement may be treated with a commercially available bonding material to provide satisfactory service. In general, full-depth replacement of contaminated asphalt pavement surfaces is the only reliable method of correction. This requirement for full-depth removal and replacement of contaminated asphalt concrete can be placed in the main body of the specifications.

When a herbicide is required the type and method of application will depend upon factors such as type of plants to be destroyed, weather conditions, time restraints, etc. Previous local construction practices that were successful should be used as a guide.

Use the paragraph on tack coat only when the pavement surface is porous (possibly due to raveling) and aged.

The following paragraphs will require editing according to the condition of the pavement to be sealed.

3.1 PREPARATION OF SURFACE

Prior to application of the sealer mixture, the existing pavement surface shall be cleaned and unsatisfactory areas repaired.

3.1.1 Repaired or New Pavement

Failed pavement, base, subbase, or subgrade material shall be removed and replaced with new materials. Areas patched or repaired with asphalt cold mix should be cured for 90 days, while those repaired with hot-mix asphalt should cure for 30 days prior to seal coating the surface.

3.1.2 Cracks

Cracks in the surface not due to structural deficiencies shall be treated as outlined below: Cracks less than or equal to 6 millimeters (1/4 inch) wide should be cleaned with compressed air. Cracks larger than 6 millimeters (1/4 inch) but less than 19 millimeters (3/4 inch) in width shall be cleaned with compressed air and filled with an approved crack sealer. Cracks larger than 19 millimeters (3/4 inch) wide shall be cleaned with compressed air and filled by squeegeeing in a mixture of aggregate and sealer. The final surface of the filled cracks shall be flush or up to 3 millimeters (1/8 inch) below the pavement surface. Any excess materials shall be removed from the pavement surface.

3.1.3 Vegetation

Vegetation existing in the cracks shall be removed by [a heat lance] [sand blasting] [water blasting] [a power driven brush] and the cracks treated with a herbicide. The type of herbicide and method of application will require approval by the Contracting Officer.

3.1.4 Oil or Fuel Contaminated Areas

Grease-contaminated and oil-contaminated areas shall be cleaned or removed and replaced with new asphalt pavement as directed by the Contracting Officer. Areas of contaminated pavement that are not removed shall be cleaned by scrubbing with a detergent and flushing with water. Areas, which cannot be satisfactorily cleaned by this manner, may be primed with material especially manufactured to provide a surface suitable for sealing.

3.1.5 Paint Removal

Areas containing loose or flaking paint or containing heavy applications of paint that could inhibit bonding shall be removed. Paint adhering to the pavement shall be removed with scrapers, wire brushes, sandblasting, approved chemicals, or mechanical abrasion, as directed by the Contracting Officer. The treated surface shall be swept, blown with compressed air, or rinsed with water as required prior to application of the sealer.

3.1.6 Tack Coat

NOTE: Delete this paragraph where application of a tack coat is not part of the manufacturer's recommended procedure. Tack coats are normally used only on very dry and porous pavement surfaces.

The pavement surface shall be prepared as specified above and sprayed with a thin coat of 3 parts water to 1 part coal-tar emulsion. The tack coat shall be applied at a rate of 0.23 to 0.45 liters per square meter [0.05 to 0.10 gallons per square yard].

3.2 MIXING AND APPLICATION OF SEALER

3.2.1 Mixing

The sealer shall be mixed as described in paragraph EQUIPMENT. The sealer mixture shall be of the desired consistency with no segregation when deposited on the surface of the pavement. The sealer mixture shall show no signs of uncoated aggregate, segregation, or premature breaking of the emulsion when applied to the pavement surface.

3.2.2 Application

NOTE: This paragraph may have to be amended
depending upon the manufacturer's recommendations.

The sealer shall be applied in such a manner that the minimum thickness will equal that given in Table 1 *Aggregate Gradation Ranges and Corresponding Minimum Sealer Mixture Application Rates*. Variation in the specified application rate of each coating shall not vary by more than plus or minus 5 percent. A minimum of two coats shall be applied with aggregate at the minimum application rate consistent with the size of the aggregate used. When practical, the coatings shall be applied perpendicular to each other. Each application shall be thoroughly cured before another application is placed.

3.2.2.1 Squeegee

Sufficient quantities of the sealer mixture shall be fed into the spreader to obtain uniform and complete pavement coverage. The spreader shall be operated at such a forward speed that the amount of sealer mixture in the spreader shall remain essentially constant. No oversized aggregate particles shall be allowed in the sealer mixture, and no buildup of cured sealer mixture shall be allowed to collect in the spreader. Streaks shall not be left in the finished surface.

3.2.2.2 Spray

The sealer shall be applied uniformly, at the required rate of application. The pump, individual spray nozzles, and other equipment on the spray vehicle shall be kept clean and working properly.

3.2.3 Hand Application

NOTE: Close attention should be given during hand squeegee spreading of an emulsion sealer mixture. Overworking will sometimes cause partial breaking of the emulsion before the final spreading is completed; this results in a non-uniform material that will have poor appearance and low durability.

Areas which cannot be reached with the application equipment, or areas with minor defects shall have the sealers applied with hand squeegees or shall be sprayed by

the wand to provide complete and uniform coverage. These areas shall be tacked and fogged as required prior to placing sealer by hand.

3.2.4 Wetting Pavement Surface

NOTE: Wetting of the surface is recommended on hot, sunny days, generally when the pavement surface temperature exceeds 43°C [110°F]. Eliminate this paragraph when it is known that the emulsion manufacturer recommends against it.

When the pavement surface temperature exceeds [43°C [110°F] pavement surface shall be moistened with a fog spray of water immediately prior to application of the sealer mixture. This requirement can be eliminated when the emulsion manufacturer provides a written recommendation against it. No free water shall be on the surface of the pavement following the fog spray. The rate of application of the fog spray shall be adjusted during the day to suit pavement temperature, surface texture, humidity, and the overall condition of the pavement surface.

3.2.5 Joints

Longitudinal joint between adjacent lanes shall have no visible overlaps, pinholes, or uncovered areas. Thick spots caused by overlapping shall be smoothed immediately with hand squeegees before the sealer mixture cures. Overlaps, which occur at transverse joints, shall also be smoothed before the sealer mixture cures, so that a uniform surface is obtained which contains no breaks or discontinuities. Joints should be made while the first coat is still workable. If fresh working is not possible, the previous coat must be cured sufficiently to support the spreader box.

3.3 CURING

NOTE: Before traffic is permitted or a second coating applied to the first, a thorough cure must be ensured. Manufacturer's recommendations should be followed in setting cure times. Generally, the thicker the coating applied, the longer the required cure period. At the application rates given in Table 1, the curing period for the application rates of the coarse aggregate mixtures versus the application rates for the fine aggregate mixtures would be about twice as long. Normally,

10 hours is sufficient for the curing; however, this may decrease to 3 to 6 hours when the pavement surface temperature exceeds 60°C [140°F].

Each coating of the sealed pavement shall be protected from traffic by barricades and markers until the seal has cured a minimum of [] hours. This time may need significant extension depending upon daily climatic changes, such as cloud cover or previous precipitation. The Contractor, at no cost to the Government, shall control traffic and repair areas damaged by traffic or from the effects of adverse weather conditions.

3.4 QUALITY ASSURANCE

The contractor shall provide a manufacturer's certification or other proof that the mixture components conform to the requirements of this specification. Materials not meeting these requirements shall be rejected. The contractor shall provide a detailed mixture design, listing the type and amounts of all materials added, that meets all the requirements given in this specification. The amount of each mixture component added for each batch of sealer mixture shall be witnessed and recorded by a representative of the Contracting Officer.

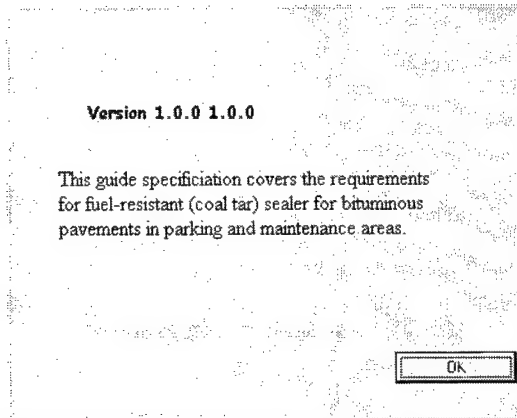
3.5 CLEANUP

Upon completion of work, all trash, discarded seal material, or other refuse shall be collected and removed from the site and disposed of as approved by the Contracting Officer.

-- End of Section --

APPENDIX E

LISTING OF EXPERT SYSTEM SELECTION SCREENS AND CORRESPONDING VISUAL BASIC CODE



Option Explicit

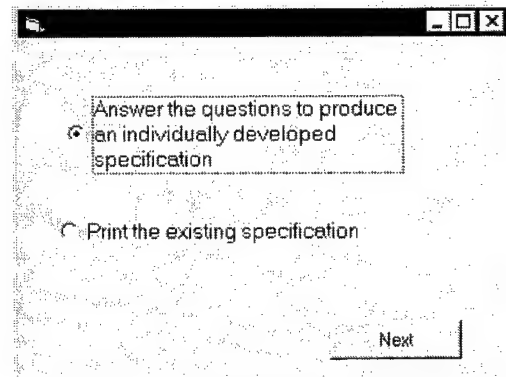
```
Private Sub Form_Load()
With App
    lbl_Title = .title
    lbl_Author = lbl_Author
    lbl_Version = lbl_Version & " " & _
        .Major & "." & .Minor & "." & _
        .Revision
End With
End Sub

Public Property Let TotalSteps(ByVal
NewValue As Byte)
cmd_OK.Visible = False
ProgressBar1.Visible = True
ProgressBar1.Max = NewValue
Show vbModeless
Refresh
End Property

Public Property Get TotalSteps() As
Byte
TotalSteps = ProgressBar1.Max
End Property

Public Function StepCompleted() As
Byte
With ProgressBar1
    .Value = .Value + 1
    If .Value = .Max Then
        DelayFor 0.25
        Unload Me
        StepCompleted = .Value
    End If
End With
End Function
```

```
End If
End With
End Function
```



Option Explicit

```
Private Sub Ok_Click()
Select Case answ

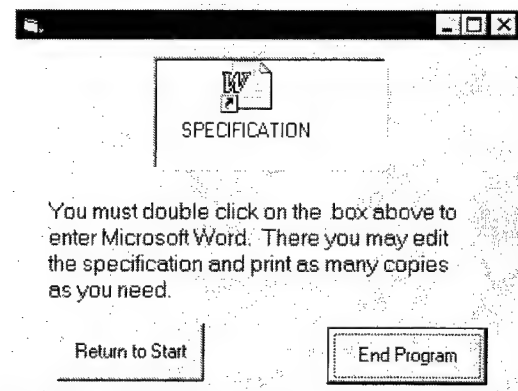
    Case 1
        Unload Me
        traffic.Show

    Case 2
        Unload Me
        Finalfirst.Show

End Select
End Sub

Private Sub Option1_Click()
answ = 1
End Sub

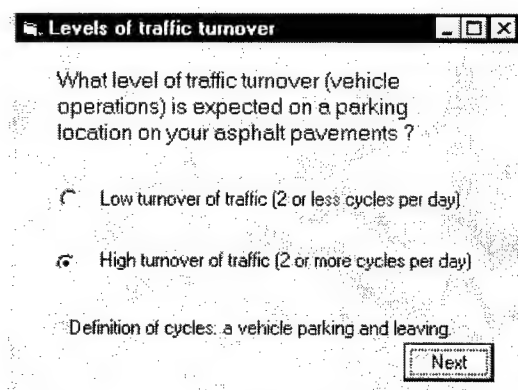
Private Sub option2_Click()
answ = 2
End Sub
```



Option Explicit

```
Private Sub Ok_Click()
Unload Me
Call cmdend
End Sub
```

```
Private Sub return_Click()
Unload Me
About.Show
End Sub
```



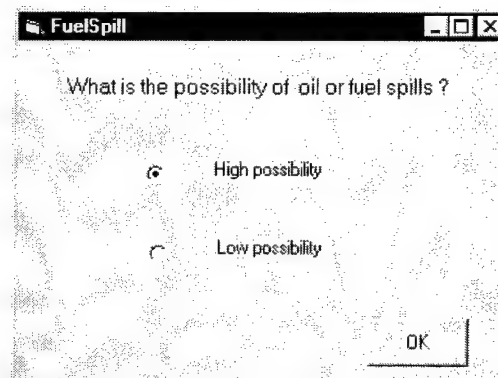
```
Option Explicit
Public ans1 As Integer
```

```
Private Sub Form_Load()
ans1 = 2
End Sub
```

```
Private Sub Ok_Click()
If ans1 = 2 Then
Unload Me
```

```
condition1.Show
Else
Unload Me
fuelSpill.Show
End If
End Sub

Private Sub Option1_Click()
ans1 = 1
End Sub
```

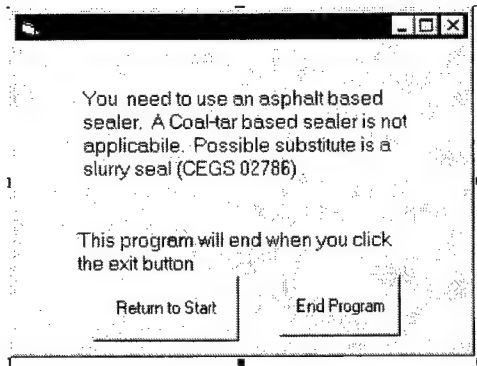


```
Option Explicit
Dim ans1 As Integer
```

```
Private Sub okay_Click()
If ans1 = 1 Then
Unload Me
condition1.Show
Else
Unload Me
SealerAsphalt.Show
End If
End Sub
```

```
Private Sub Option1_Click()
ans1 = 1
End Sub
```

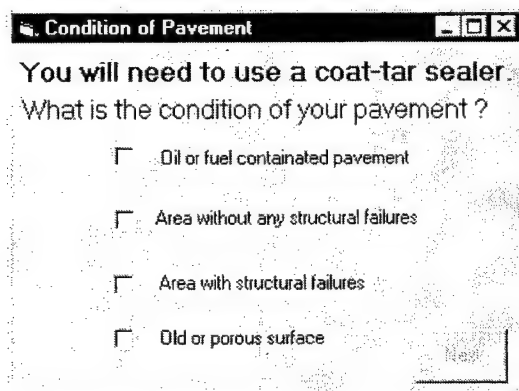
```
Private Sub option2_Click()
ans1 = 2
End Sub
```



Option Explicit

```
Private Sub End_Click()
    End
End Sub
```

```
Private Sub start_Click()
    Unload Me
    About.Show
End Sub
```



Option Explicit

```
Private Sub Check1_Click()
    OK.Enabled = True
    oilnote.Show
End Sub

Private Sub Check2_Click()
    OK.Enabled = True
    Check3.Enabled = False
End Sub

Private Sub Check3_Click()
```

```
    OK.Enabled = True
    Check2.Enabled = False
End Sub
```

```
Private Sub Check4_Click()
    OK.Enabled = True
    oldnote.Show
End Sub
```

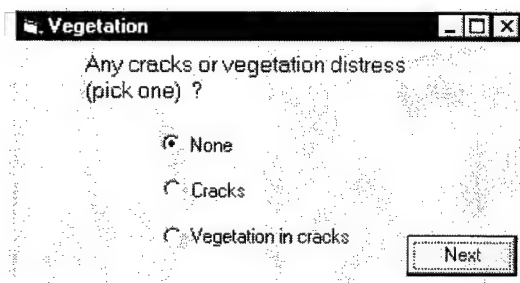
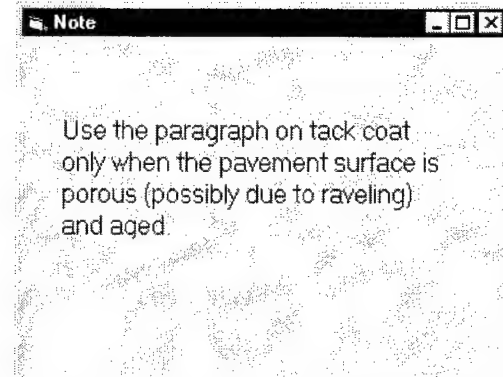
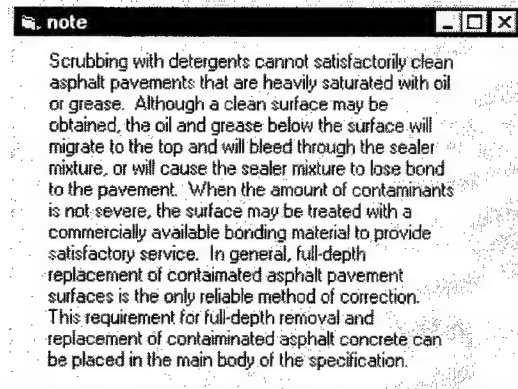
```
Private Sub Form_Load()
    OK.Enabled = False
End Sub
```

```
Private Sub Ok_Click()
    If Check1.Value = 1 Then
        oil = 1
    Else
        oil = 0
```

```
    End If
    If Check2.Value = 1 Then
        sound = 1
    Else
        sound = 0
    End If
    If Check3.Value = 1 Then
        fractured = 1
    Else
        fractured = 0
```

```
    End If
    If Check4.Value = 1 Then
        oldnote.Show
        old = 1
    Else
        old = 0
    End If
```

```
    Unload Me
    Unload oldnote
    Unload oilnote
    Vegetation.Show
End Sub
```



Option Explicit
Dim answ2 As Integer

```
Private Sub Form_Load()
    answ2 = 1
End Sub
```

```
Private Sub Ok_Click()
    If answ2 = 1 Then
        None = 1
    Else: None = 0
    End If
    If answ2 = 2 Then
        crack = 1
    Else: crack = 0
    End If
    If answ2 = 3 Then
        veggie = 1
        crack = 1
    Else: veggie = 0
    End If
End Sub
```

End If

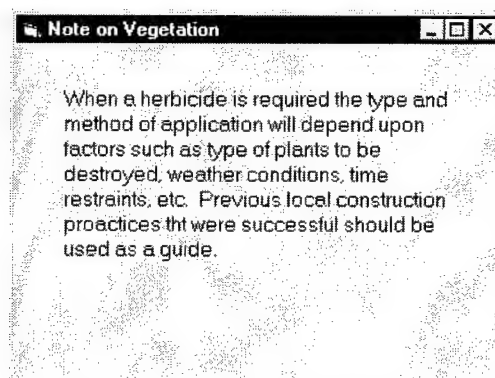
Unload Me
Unload vegnote
paint.Show

End Sub

```
Private Sub Option1_Click()
    answ2 = 1
End Sub
```

```
Private Sub option2_Click()
    answ2 = 2
End Sub
```

```
Private Sub Option3_Click()
    answ2 = 3
    vegnote.Show
End Sub
```



Paint removal

Any paint striping to be covered ?

☒ Loose or flaking paint or large areas with a heavy application of paint to prevent bonding.

☐ No loose or flaking paint or large areas with heavy applications of paint to prevent bonding.

☐ No paint

Next

Option Explicit
Dim answ1 As Integer

```
Private Sub okay_Click()
Select Case answ1
Case 1
    repaint = 1
Case 2
    repaint = 0
Case 3
    repaint = 0
End Select
Unload Me
Surfcondition.Show
End Sub
```

```
Private Sub Option1_Click()
    answ1 = 1
End Sub
```

```
Private Sub option2_Click()
    answ1 = 2
End Sub
```

```
Private Sub Option3_Click()
    answ1 = 3
End Sub
```

Overall Surface condition

What is the overall condition of the pavement ?

☐ No measurable pavement surface variations (no deviations larger than 6 mm (1/4 in.) when measured from a 3.7 m (12 ft.) straightedge)

☒ Pavement surface variations larger than 6mm (1/4 in.) when measured from a 3.7 m (12 ft.) straightedge.

Next

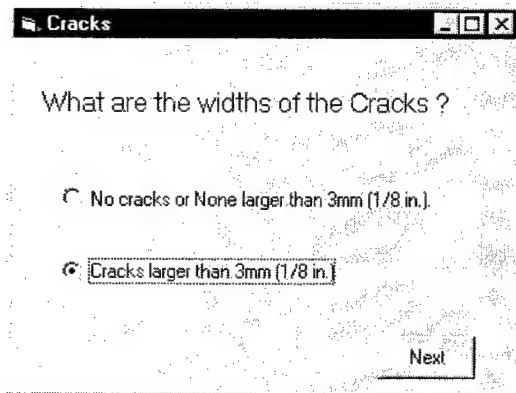
Option Explicit
Private answ3 As Integer

```
Private Sub Form_Load()
    answ3 = 2
End Sub
```

```
Private Sub Ok_Click()
If answ3 = 1 Then
    smDev = 1
End If
If answ3 = 2 Then
    lgDev = 1
End If
If crack = 1 Then
    Unload Me
    surfcond2.Show
ElseIf crack = 0 Then
    If smDev = 1 Then
        Unload Me
        tools.Show
    ElseIf lgDev = 1 Then
        Unload Me
        squeege.Show
    End If
End If
End Sub
```

```
Private Sub Option1_Click()
    answ3 = 1
End Sub
```

```
Private Sub option2_Click()
    answ3 = 2
End Sub
```



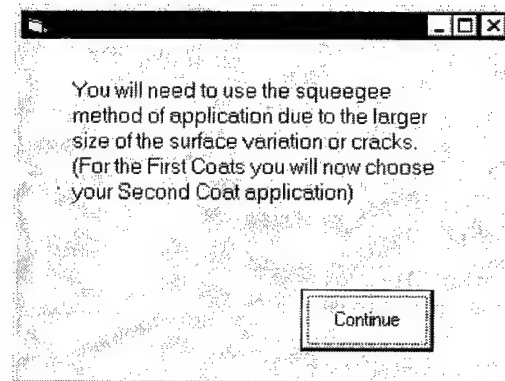
Option Explicit
Private answ As Integer

```
Private Sub Form_Load()
    answ = 1
End Sub
```

```
Private Sub Ok_Click()
    If answ = 1 Then
        smDev = 1
        Unload Me
        tools.Show
    Else
        lgDev = 1
        Unload Me
        squeegee.Show
    End If
End Sub
```

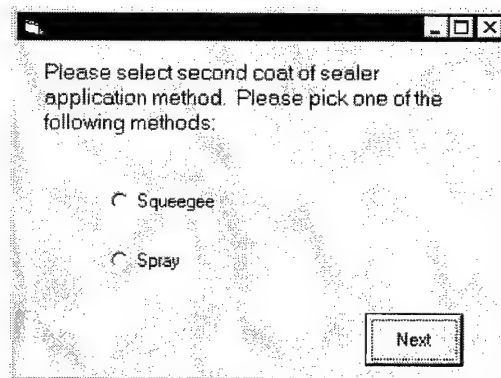
```
Private Sub Option1_Click()
    answ = 1
End Sub
```

```
Private Sub option2_Click()
    answ = 2
End Sub
```



Option Explicit

```
Private Sub Continue_Click()
    squeegee1 = 1
    Unload Me
    secCoat.Show
End Sub
```



Option Explicit
Dim answ As Integer

```
Private Sub Ok_Click()
    Unload Me
    term.Show
End Sub
```

```
Private Sub Option1_Click()
    answ = 1
    squeegee2 = 1
    spray2 = 0
    If squeegee1 = 1 Then
        squeegeonly = 1
    End If
```


End Sub

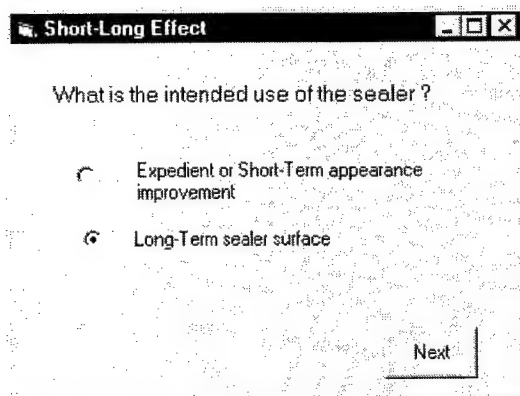
Private Sub option2_Click()

answ = 2

spray2 = 1

squeegee2 = 0

End Sub



Option Explicit

Dim term As Integer

Private Sub Ok_Click()

Select Case term

Case 1

Unload Me

tempques.Show

Case 2

NoPoly = 1

Unload Me

expedient.Show

End Select

End Sub

Private Sub Option1_Click()

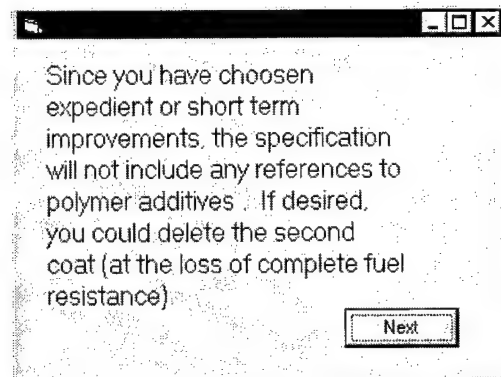
term = 1

End Sub

Private Sub option2_Click()

term = 2

End Sub



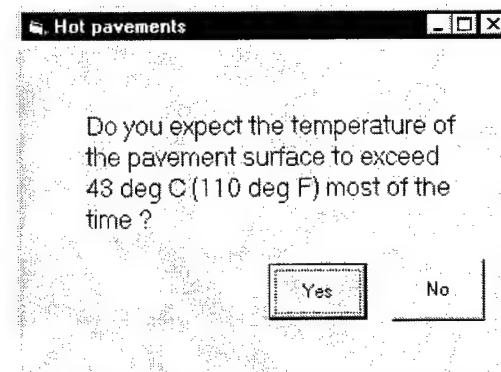
Option Explicit

Private Sub Ok_Click()

Unload Me

tempques.Show

End Sub



Option Explicit

Private Sub No_Click()

hot = 0

Unload Me

temperature.Show

End Sub

Private Sub Yes_Click()

hot = 1

Unload Me

temperature.Show

wettempnote.Show

End Sub

Option Explicit

```
Private Sub Form_Load()
```

```
    If hot = 1 Then
```

```
        Option2 = True
```

```
    Else
```

```
        Option4 = True
```

```
    End If
```

```
End Sub
```

```
Private Sub Ok_Click()
```

```
    Unload Me
```

```
    Unload wettempnote
```

```
    aggregate.Show
```

```
End Sub
```

```
Private Sub Option1_Click()
```

```
    temp = 1
```

```
End Sub
```

```
Private Sub option2_Click()
```

```
    temp = 2
```

```
    wettempnote.Show
```

```
End Sub
```

```
Private Sub Option3_Click()
```

```
    temp = 3
```

```
    wettempnote.Show
```

```
End Sub
```

Option Explicit

```
Dim answ As Integer
```

```
Private Sub No_Click()
```

```
    hot = 0
```

```
    temperature.Show
```

```
End Sub
```

```
Private Sub Yes_Click()
```

```
    hot = 1
```

```
    temperature.Show
```

```
End Sub
```

Option Explicit

```
Dim answ As Integer
```

```
Dim wonga As Long
```

```
Dim wongb As Long
```

```
Dim i As Long
```

```
Dim thereitis As Long
```

```
Dim curetime As String
```

```

Private Sub Form_Load()
    gradationnote.Show
    answ = 2
End Sub

Private Sub Table1_Click()
    Unload Me
    table.Show
End Sub

Private Sub Ok_Click()
    Select Case answ
        Case 1
            Select Case temp
                Case 1
                    curetime = "ten(10)"
                Case 2
                    curetime = "eight(8)"
                Case 3
                    curetime = "six(6)"
            End Select
        Case 2
            Select Case temp
                Case 1
                    curetime = "eight(8)"
                Case 2
                    curetime = "six(6)"
                Case 3
                    curetime = "four(4)"
            End Select
        Case 3
            Select Case temp
                Case 1
                    curetime = "six(6)"
                Case 2
                    curetime = "four,five(4,5)"
                Case 3
                    curetime = "three(3)"
            End Select
    End Select
    If temp = 1 Then
        wonga = Len(HandLowTemp)
        For i = 1 To wonga
            If Mid(HandLowTemp, i, 1) =
"&" Then thereitis = i
        Next i
    End If

```

```

        HandLowTemp =
Left(HandLowTemp, thereitis - 1) +
curetime + Right(HandLowTemp,
wonga - 9 - thereitis)
    Else
        wongb = Len(HandToCure)
        For i = 1 To wongb
            If Mid(HandToCure, i, 1) =
"&" Then thereitis = i
        Next i

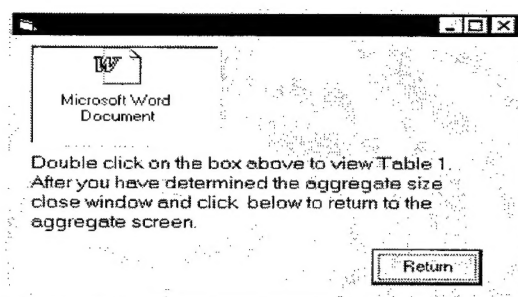
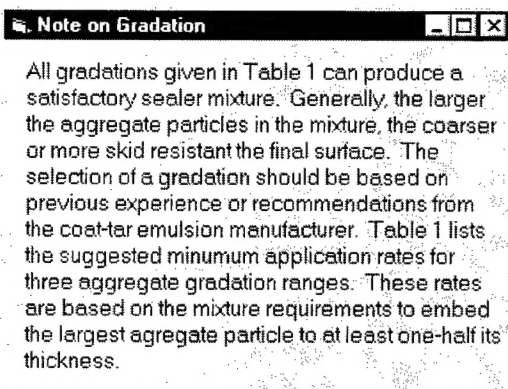
        HandToCure =
Left(HandToCure, thereitis - 1) +
curetime + Right(HandToCure, wongb
- 9 - thereitis)
    End If
    If NoPoly = 1 Then
        Unload Me
        Unload gradationnote
        final.Show
    End If
ElseIf smDev = 1 Then
    Unload Me
    Unload gradationnote
    mixdesign1.Show
ElseIf lgDev = 1 Then
    Unload Me
    Unload gradationnote
    mixdesign2.Show
End If
End Sub

Private Sub Option1_Click()
    answ = 1
End Sub

Private Sub option2_Click()
    answ = 2
End Sub

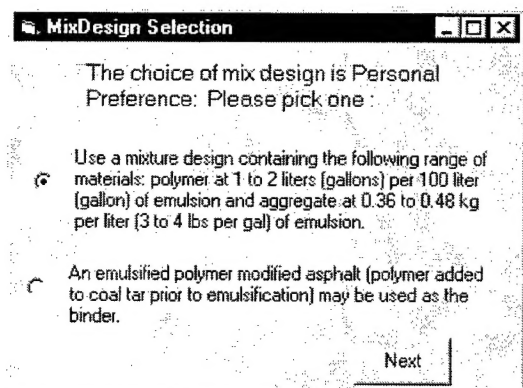
Private Sub Option3_Click()
    answ = 3
End Sub

```



Option Explicit

```
Private Sub Ok_Click()
    Unload Me
    aggregate.Show
End Sub
```



Option Explicit

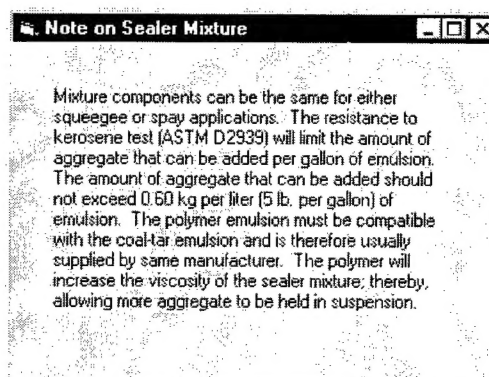
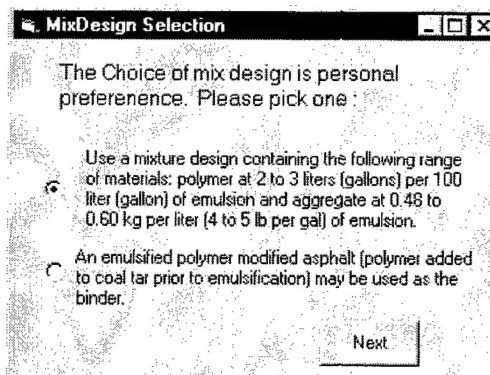
Option Explicit

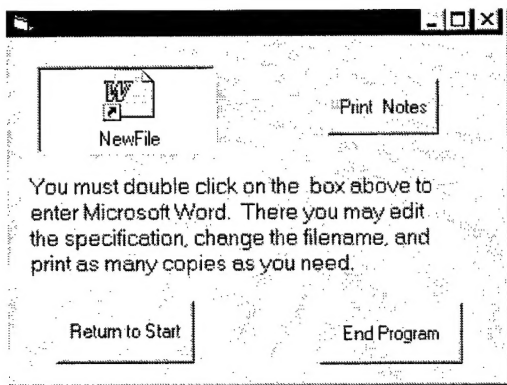
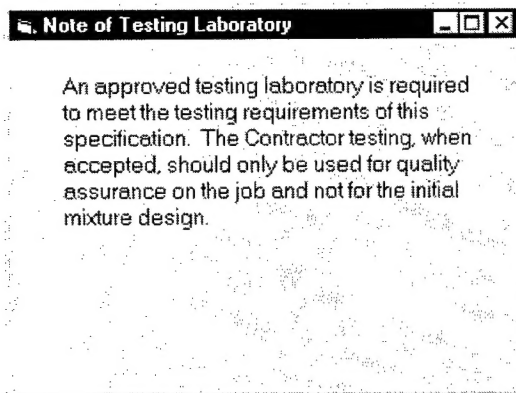
```
Private Sub Form_Load()
    sealernote.Show
    laboratorynote.Show
End Sub
```

```
Private Sub Ok_Click()
    Unload Me
    Unload sealernote
    Unload laboratorynote
    final.Show
End Sub
```

```
Private Sub Option1_Click()
    mixdesign = 1
End Sub
```

```
Private Sub option2_Click()
    mixdesign = 2
    NoEmulPoly = 1
End Sub
```





Option Explicit

Private Sub Bye_Click()

Unload Me

Call maketext

Call printtext

Call cmdend

End Sub

Private Sub Form_Load()

Call wrightit

End Sub

Private Sub okay_Click()

Unload Me

About.Show

End Sub

REPORT DOCUMENTATION PAGE

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14. ABSTRACT Coal-tar sealers are used to protect asphalt pavements from damage by fuel spillage. The useful life of coal-tar sealers has been limited by cracking in both trafficked and non-trafficked areas and in all climatic regions. Several coal-tar mixtures that varied with source of the coal-tar emulsion, amount of aggregate, and amount of polymer used in the mixtures were evaluated for their field performance and material properties. The material properties of these mixtures were determined through curing, thermal, bending, tensile, and stress-relaxation testing. The material properties were determined using testing and evaluation methods either adapted from previous work or developed for this research. The results of the evaluation showed that two coal-tar emulsion sealers meeting all current applicable specifications could have substantially different field performance. The amount of aggregate and polymer on the coal-tar mixtures will affect the sealer's performance. The sealer mixtures age or harden over time and cracking occurs through thermal movements resulting in a build up of stresses that the sealer cannot relax or dissipate. Generally, mixtures with higher amounts of aggregate and at least some polymer (acrylonitrile-butadiene) performed the best. (Continued)					
15. SUBJECT TERMS Coal tar Coal-tar emulsion		Coal-tar sealer Expert system Fuel-resistant sealer		Pavement sealer	
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14. ABSTRACT (continued)

The information gained during the field and laboratory evaluation of the various sealer mixtures was used to develop an expert system for specifying coal-tar sealers. The expert system provides a practical method for an engineer/designer to develop a systematic approach to selecting the type of sealer, material and design considerations, and construction methods. A guide specification that incorporates recommended test methods, materials, and application procedures are included as an appendix. The use of this system and guidelines is intended to provide an optimum coal-tar sealer mixture.